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THE MINERALOGRAPHY OF THE FELDSPARS
PART II—(*Concluded*)

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THE SODA-LIME SERIES

The problem of the isomorphism of the plagioclase feldspars has not been fully understood. That they are a series of solid solutions is a matter upon which there is little disagreement, but how can albite and anorthite be isomorphous? On this question Wherry[1] has reached the conclusion that it is a case of atomic isomorphism, with one aluminum atom occupying a sort of nuclear position in both end-members; the second aluminum atom of anorthite being definitely a replacement of one silicon atom of albite. This is indicated by the formulas: $NaAl(Si_3O_8)$ and $CaAl(AlSi_2O_8)$.[2]

[1] E. T. Wherry, "The Plagioclase Feldspars as a Case of Atomic Isomorphism," *Amer. Min.*, Vol. VII, No. 7 (July, 1922), 113–21.

[2] The Asches in *The Silicates in Chemistry and Commerce*, p. 295, say: "Tschermak assumed that the [plagioclase] feldspars were isomorphous mixtures of two silicates—albite and anorthite—to which he gave the following formulas: Albite $NaAlSiSi_2O_8$; Anorthite $CaAlAlSi_2O_8$." If this is correct, the idea expressed by Wherry is not a new one at all and the credit should be given to Tschermak. See E. T. Wherry, "Volume Isomorphism in the Silicates." *Amer. Min.*, Vol. VIII (1923), pp. 2–3. F. Zambonini (H. S. Washington), "The Isomorphism of Albite and Anorthite," *Amer. Min.*, Vol. VIII (1923), pp. 81–85. T. Sterry Hunt, *Amer. Jour. Sci.*, Vol. XVIII (1854), p. 270; *Phil. Mag.*, Vol. IX (1855), p. 354.

It is a little difficult to understand why the majority of American mineralogists seem to favor the view that the two silicate radicals (Si_3O_8) and (SiO_4) are mutually equivalent. It was an oversight, however, for Wherry to include the writer in this group.

The writer believes that Wherry has reached a very reasonable explanation of the isomorphism of the series.

THE POTASH-LIME SERIES

This system, called the "oranite" series in Part I, is the one that is rarely recognized. Several illustrations, however, from the Adirondacks were there recorded. Such feldspars are intergrowths and mechanical aggregates, not homogeneous single-phase solid solutions.[1]

Wherry[2] in the July and October numbers of the *American Mineralogist* took exception to some of the statements in Part I. These criticisms, based upon misunderstandings, have been reconsidered and corrections have been made in the December number.[3] We are essentially in agreement.

Oranite is not a hypothetical intergrowth. A dozen slides in the writer's collection contain examples. Furthermore various investigators, including Dittler[4] and the writer, have succeeded in synthesizing them in the laboratory. They correspond to *perthite*.

The reason for giving this system a name is as follows: The Adirondack occurrences consist of labradorite ($Mi_5Ab_{45}An_{50}$) with blebs of potash feldspar ($Or_{85}Ab_5An_{10}$) imbedded in it. This intergrowth is approaching, as a limit, the potash-lime binary system; hence a name is very desirable and quite analogous to perthite.

The results of thermal studies on artificial feldspars by the investigators above mentioned show that on adding orthoclase to bytownite or to anorthite zonal grown crystals can be made up to 10–15 per

[1] See page 236 of Part I. See Harker, *op. cit.*, p. 246; William S. Bayley, *Descriptive Mineralogy*, 1917, p. 408.

[2] E. T. Wherry, *Amer. Min.*, Vol. VII, No. 7 (July, 1922), p. 115. Also Wherry misquotes the writer in *Rev. Geol.*, January, 1923, p. 30, No. 22.

[3] E. T. Wherry, *Amer. Min.*, Vol. VII, No. 12 (December, 1922), p. 212.

[4] Emil Dittler, "Über die Darstellung kalihaltiger basischer Plagioklase," *Min. und Petro.*, Neue Folge., XXIX (1910), 273–333; "Über das Verhalten des Orthoklase zu Andesin und Celsian über seine Stabilität in künstlichen Schmelzen," *Min. Petr. Mitt.*, XXX (1911), 118–27.

cent of orthoclase but beyond that amount the cooled material consists of two phases. The maximum separation of the potash-rich and the lime-rich feldspars occurs at about 45 per cent Or, 55 per cent An. It is not the intention of the writer to convey the idea that the results of these thermal studies prove that this percentage fixes the position of the eutectic point, but only that it is probably in this neighborhood. An artificial mixture of 40 per cent orthoclase, 20 per cent albite, 40 per cent anorthite, when held at 1250° C. for several hours and then cooled rapidly showed a pseudohomogeneous solid solution, a crypto-oranite (to parallel Brögger's "cryptoperthite"). This sample when "annealed" at a lower temperature for a longer time became a micro-oranite, consisting of two phases. This separation became more perfect as the time of annealing was extended. Similar treatment of anorthoclase gave no such results. The interpretation of these observations is that the viscosity of the lime-free feldspars prevents extensive separation of the two phases. But with increased lime the viscosity of the melt is proportionally lower, allowing a greater separation.[1]

The petrogenetic significance of this is that magmas which contain potential oranitic feldspar give rise to two-phase systems consisting of orthoclase-rich and plagioclase-rich feldspar. This applies to many granites, syenites and monzonites. The presence of such potential oranitic feldspars in the common rocks is often concealed by recasting the chemical analysis into the *norm*, and while it is not so easy to secure the *mode* of an igneous rock, the latter alone shows the real distribution of the feldspar components into their respective phases. Such a procedure is necessary to obtain a true conception of the nature of the feldspars in many rocks.

The reader may observe that the writer is extending the meaning of the term "oranite" to cover molten feldspar mixtures. We are so much in the habit of considering our minerals as solid substances (the usual definition) that we lose sight of the manner of their crystallization. To give to these feldspathic melts a definite name emphasizes their existence, and leads us to be on the lookout for the end-products of such processes.

[1] A. L. Day and E. T. Allen, "The Isomorphism and Thermal Properties of the [Plagioclase] Feldspars," *Carnegie Inst. Pub. 31* (1905).

THE ZONING OF FELDSPARS

It was Hoepfner[1] who first called attention to zonal structures in plagioclase. Rosenbusch[2] early explained it as due to periodic interruptions during crystallization and to selective decomposition. Michel-Levy[3] considered zonals as "the result of a submicroscopic twin lamination after the albite and pericline laws." Later Rosenbusch showed that in many cases the kernel of a zonal is more basic than that of the shells. He explained this on the basis that there exists an isomorphous lamination in which an original, basic, central crystal is surrounded by shells of other plagioclase which gradually become more and more acid. The great majority of zonals can be fully understood by following the crystallization of a melt by means of a thermal diagram. The phenomenon is not confined to feldspars nor to isomorphous minerals; it is also found in many alloys.[4]

In deep-seated rocks zonals are not common, nor do they occur in glassy rocks. Yet in certain porphyritic rocks zonal feldspars are frequently found. This simple observation has an important genetic significance. In Part I, page 215, the statement is made that the degree of homogeneity is a function of the rate of chill. Bowen[5] says: "There is a certain definite rate of cooling which gives maximal zoning. . . . . With a somewhat quicker rate of cooling, the range of zoning is not so great owing to a moderate degree of undercooling, and when the undercooling is very great there is no zoning at all." This relation is graphically expressed by Figure 7 which, of course, is to be interpreted qualitatively and not quantitatively. We can make use of this observation in arriving at the conditions under which rocks of this kind solidified.

[1] C. Hoepfner, "Über das Gestein des Mte. Tajumbia in Peru," *N. Jahrb. f. min. u. geol.*, II (1881), 164–92; J. Blumrich, *Tscher. Min. u. Petro. Mitt.*, XIII (1892), 239, 258; A. Pelikan, *ibid.*, XVI (1896), 1.

[2] Rosenbusch-Iddings, *Microscopical Physiography of the Rock Making Minerals*, pp. 307, 326.

[3] A. Michel-Levy, *Comp. Rendu*, XCIV (1882), 93, 178.

[4] Edgar Bain, "Cored Crystals and Metallic Compounds," *Chem. and Met. Eng.*, Vol. XXVIII, No. 2 (January 10, 1923), 65–69; Walter Rosenhain, *ibid.*, No. 10 (March 7, 1923), 442–46; *Trans. Amer. Inst. Min. and Met. Eng.*, June, 1923.

[5] N. L. Bowen, *Jour. Geol. Suppl.*, XXIII (No. 8, 1915), 33.

Zonal feldspars are not exclusively plagioclase, for orthoclase, microcline, and anorthoclase occur with this structure. "In certain porphyritic granites (Rapakiwi) oligoclase forms a shell about phenocrysts of orthoclase."[1]

THE TWINNING OF FELDSPAR

It seems a pity that while the twinning phenomena of feldspars are listed and illustrated in every textbook of any pretensions, no adequate theory is offered in explanation. Harker,[2] following Vogt,[3] has stated that microcline structure seems "to be sufficiently accounted for by spontaneous changes consequent upon fall of temperature," a view maintained in Part I. Still the setting up of microclinic structure is also a function of stress.[4] The two ideas can be united by saying that the inversion of orthoclase to microcline (if we grant dimorphism) involves a change in volume[5] and this introduces stress into the system. Now it is conceivable that inversion may take place and a change in volume ensue, but at such a slow rate that twinning does not occur. The writer has repeatedly observed in cutting and grinding feldspars for thin sections that microcline twinning is produced by the process. Hence he reasoned that gentle and slow grinding might result in a section free from twinning. This proved to be correct after repeated failures. The microcline from Lincoln County, Nevada, thin sectioned in this careful manner, showed the following extinction angles, (010) 5.6°, and (001) 16.1° *although exhibiting no microcline twinning*, even when magnified to 2,400 diameters. An ordinary slide of the same specimen showed "scotch plaid" structure and the same extinction angles. Iddings[6] says "Microcline . . . . may be free from lamellar twinning and resemble orthoclase except in its optical orientation." The conclusion is clear: that microcline twinning is not always characteristic of microcline but merely of a strained condition

[1] J. P. Iddings, *Igneous Rocks*, II, 47.

[2] *Op. cit.*, p. 260.

[3] Vogt, *Tsch. Min. Petr. Mitt.* (2), XXIV, 537–41.

[4] See Part I, pp. 275–76.

[5] Note the two sets of specific gravities for potash-soda feldspars.

[6] *Op. cit.*, p. 46.

perhaps due to volume change on inversion. Or it may be that microcline and plagioclase twinning are often produced by stress in making thin sections. Incipient twinning may always be present in plagioclase or microcline as a result of atomic arrangement. If it is very minute it may be exaggerated by stress to a point where it can be seen.

> Many years ago . . . . George W. Hawes[1] noticed in slides of . . . . [anorthosite] some feldspars which failed to afford the twinning striations, yet which he suspected of being plagioclase. Analytical tests demonstrated that they were. The same untwinned character may reappear so that the observer must be on his guard, but it is also true that a chance section parallel to the twinning plane would be without striations.[2]

In some cases ordinary slides of normal andesine, labradorite and especially bytownite show no twinning at all. The feldspars are clear and so similar to orthoclase under the microscope that unless extinction angles or, better still, the indices of refraction are determined it may well pass for that mineral. This development of twinning by pressure is more noticeable in albite ranges and decreases in intensity as the lime range is approached. The bytownite from Crystal Bay, Minnesota[3] ($Mi_{2.0}Ab_{24.7}An_{73.3}$) when thin-sectioned with great care is entirely free from twinning, while an ordinary slide prepared by Tomlinson exhibited broad albite twinning. Thus the writer would voice a word of caution: All feldspars may occur in thin section absolutely untwinned and hence the presence or absence of twinning is not a reliable means of identification.

POTASH-SODA-LIME FELDSPARS

In Part I the writer maintained that all natural feldspars are systems of three components and should, when elaboration demands, be recorded as such (cf. the composition of the feldspars here discussed). Professor A. N. Winchell has kindly called my attention to the fact that Sabot[4] reached that conclusion in 1915. Sabot says (in an abstract in translation):

[1] George W. Hawes, "On the Determination of Feldspars in Thin Sections of Rocks," *U.S. Nat. Mus. Proc. 1882*, IV, 134–36.

[2] J. F. Kemp, *New York State Mus. Bull. 138* (1910), 30.

[3] Specimen 969B.

[4] R. Sabot, *Compte Rendu des Séances de la Société de Physique et de l'Histoire Naturelle de Génève*, XXXV (1918), 72; XXXVII (1919), 51.

Using the data and the graphic methods of Professors Nitikin and Koloulsky . . . . , in spite of the fine precision in their work, the points of the curves of the representative feldspars were not exactly upon the published curves of either Michel-Levy[1] or those of Nikitin. The deviation is to be explained by the presence, in the plagioclase series, of the term $KAlSi_3O_8$, triclinic, frequently entering [into the composition] in notable quantities. The published data of the feldspars, for example that of the extinction [angles] for a determined face, should not be distributed upon a curve, but be spread more or less over an area, according to the proportion of the potash [component] present.

Fedorow[2] said that "Another question which the law of Tschermak is not competent to explain[3] is the presence of potassium often in notable proportions in the majority of plagioclases."[4]

J. Schetelig,[5] in speaking of the discrepancy between the optical and chemical determination of the composition of an albite says:

The difference is due either to small errors in the exact orientation of the sections and in the determination of the angles of extinction, or *to the hitherto not exactly known influence of the relatively large amount of the Or-component on the optical properties of the plagioclases.* [The writer's italics.] The tables of F. Becke for computation of the composition of the plagioclase are based upon careful investigation of pure mixtures of the Ab- and An-components, but the influence of the Or-component is not taken into consideration.

If there should be a series of thermal diagrams instead of a single binary one to show the crystallization of the potash-soda series so that all potash-soda feldspars, no matter of what origin, could be fully understood, then there should be a group of three dimensional models to show all possible feldspars consisting of three components. While the phenomenon of undercooling is especially noticeable in the case of the potash-soda series, we should not forget that the other

[1] E. S. Larsen, in a review of Johannsen's recent *Essentials for the Microscopical Determination of Rock-forming Minerals* (*Eng. and Min. Journal-Press*, Vol. 114, No. 18 [October 28, 1922], p. 775), says: "It is regrettable . . . . that for the Michel-Levy method the old diagram has been used. Determinations made by this diagram are commonly in error as much or even greater than 10 per cent, whereas by using the diagram published by Wright the determinations check with those made by other methods."

[2] E. von Fedoroff (Fedorov, Fedorow), "Universalmethode und Feldspathstudien," *Zeitschr. f. Kryst. Min.*, XXIX, 604.

[3] This criticism is too severe. Tschermak would consider the potash feldspar to be *partially* isomorphous with soda and lime components.

[4] As cited by Elvira Carrasco, "Contribution à l'étude des macles de feldspaths au moyen de la méthode de Fedoroff," *Bull. Soc. Vaud. Sc. Nat.*, LII, 483–564.

[5] Adolf Hoel and J. Schetelig, *Nephelin-Bearing Pegmatitic Dykes in Seiland*, 1916.

feldspars outside of the anorthoclase-cryptoperthite ranges exhibit the same phenomenon, although to a lesser degree. As has been

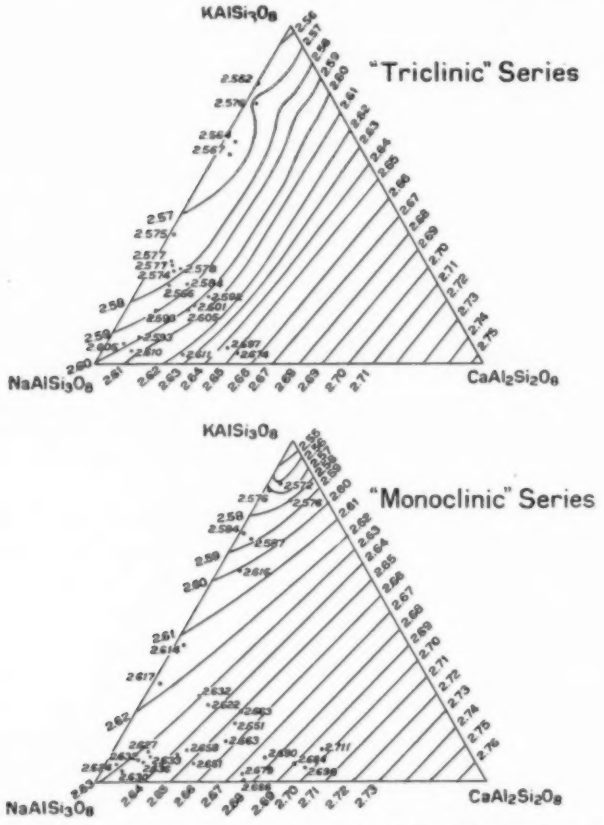

FIG. 4.—Plot of specific gravities of the potash-soda-lime feldspars shown by isogravity lines. Upper figure: Microcline, albite, anorthite, "triclinic" series. Lower figure: Orthoclase, "barbierite" and "barbierite"-rich anorthite, "monoclinic" series. Offered with full knowledge that they leave much to be desired.

already stated, the degree to which they undercool is dependent upon their origin; consequently it follows that the position of the solubility lines (perhaps best appreciated when projected to the

triangular base) is controlled by the conditions prevailing during crystallization. These lines are farther away from the sides of the diagram when excessive undercooling obtains, in fact they may come together near the center as in certain anorthoclases, producing a

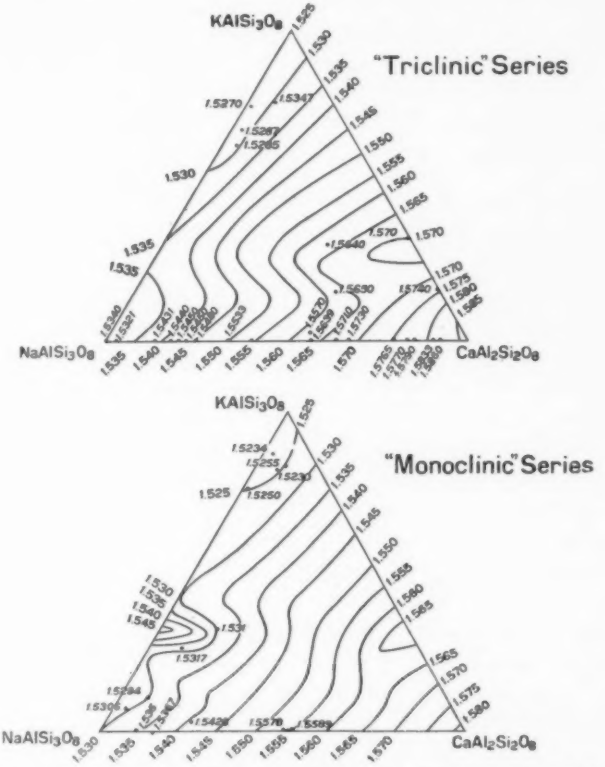

FIG. 5.—Plot of β values of indices of refraction of the potash-soda-lime feldspars. These diagrams are to be regarded as tentative and subject to revision.

series of solid solutions with a minimum, or may be close to the sides when equilibrium and exsolution are unhampered. Rapidly cooled albites, andesines, and oligoclases may thus contain a higher percentage of the potash component than the more slowly cooled equivalents. As the viscosity of such melts decreases with increased

lime it is evident that the solubility lines of the more basic plagioclases maintain a more constant position irrespective of the rate at which they have been cooled than do those of the alkali-rich feldspars. Thus we can expect to encounter such feldspars as potash-oligoclase more frequently than potash-bytownite.

It becomes necessary, therefore, to project all plotted data, specific gravities, extinction angles, indices of refraction, optical angles, crystallographic angles, etc., upon a triangular base and employ contours. Figures 4, 5, and 6 represent a revision and extension of the work suggested in Part I.

SPECIFIC GRAVITIES

The diagrams of the specific gravities of feldspars given in Part I (Figs. 12-6 and 12-7, p. 250) were only tentative, hence the effort is now made to improve their quality as it is believed thay may be of value to petrographers and mineralogists. The writer tabulated all of the available analyses of feldspars of which the specific gravities were given. These analyses were then recast into three components. This information is to be taken with caution in that many of the chemical analyses are undoubtedly inferior to those demanded today. Although the writer wishes he possessed the skill, the facilities and the time to secure afresh this needed information, he was forced to make use of these rather uncertain data.

From these data a "peg model" was constructed which clearly showed two sets of pins, one for the "monoclinic" and the other for the "triclinic series." The results of this study are given in Figure 4.

INDICES OF REFRACTION

A similar "peg model" was constructed from analogous data giving the beta values of the index of refraction of the potash-soda lime feldspars. Here the data is less comprehensive and the difficulties of the interpretation are consequently greater. At first it was thought that it was not possible to recognize two sets of pins, representing the two series, and as a result the contoured surface of the plaster model made from the peg model was most irregular. Experience with the specific gravity peg model led the writer to attempt to classify the pins into two sets, each representing a sur-

face. Whether there are two distinct sets or not is a question still to be investigated. However, their classification into two groups, depending upon their height, did result in two contoured surfaces which are reasonably regular. These diagrams are offered with the full appreciation that they leave much to be desired. Slight modifications of some of the values were necessary in order to make them "fit." The majority of the analyses of plagioclase lacked the determination of K_2O. In these cases the writer assumed the per cent of the potash component to be from 2 to 4 per cent. Larsen[1] has measured the indices of the plagioclase series and recorded the results as $\frac{\alpha+\beta+\gamma}{3}$. This curve has been modified so as to agree more closely with the curves of Rosenbusch-Wülfing,[2] Wright,[3] and Tsuboi.[4] It was also found that Dittler's[5] gamma values of synthetic oranitic feldspars, when lowered to the probable beta values were too low and they were arbitrarily raised by adding from .003 to .005 to them. In a similar way it was found that Wright's[6] *molecular* percentage curve when translated into the more usable *weight* percentage form was lower than those for most natural feldspars. Even the curves of Iddings[7] and of the Winchells[8] seem to give more consistent results on natural specimens, though there is every reason to believe that Wright's data on synthetic material is more accurate. The real point is that the average petrographer deals with natural and not with artificial minerals. The cause of these discrepancies may be explained by the lack of "impurities" such as magnesia and iron in the synthetic material. It is to be regretted that because of the paucity of accurate determinations of the physical constants of synthetic minerals we are compelled to

[1] E. S. Larsen, *Amer. Jour. Sci.*, XXVIII (1909).

[2] As given by Albert Johannsen, *Essentials for the Microscopical Determination of Rock-Forming Minerals and Rocks*, 1922.

[3] Fred E. Wright, *Am. Jour. Sci.* (4), XXXVI (November, 1913).

[4] Given by Albert Johannsen. Tsuboi, *Jour. Geol. Soc. Tokyo*, XXVII (1920), in Japanese.

[5] E. Dittler, *Tsch. Min. Petro. Mitt.*, XXIX, 39 and 387.

[6] Fred E. Wright, *Amer. Jour. Sci.* (4), XXXVI (November, 1913), 540.

[7] J. P. Iddings, *Rock Minerals*.

[8] N. H. and A. N. Winchell, *Elements of Optical Mineralogy*, 1909, p. 200.

modify such results in order to make them commensurate with the values of natural minerals.

To supplement the available data secured from the literature on the subject, the writer has measured the indices of refraction of a number of critical feldspars, by a development of the refractive index liquid immersion method.[1]

We find a serious difficulty in that some feldspars are mixtures of two different series. Foerstner has pointed out that such feldspars actually occur. When this is the case the indices are intermediate in value. The beta values of such feldspars when their indices are plotted will not lie on a surface but in a zone or a "stratum" of values. If a sufficient number of pegs has been available then the maximum and minimum values would give the two surfaces—one for "monoclinic" and the other for "triclinic" feldspars. Until

[1] The index of such oils is lowered in value with a rise in temperature while that of the feldspars rises as they are heated.

See C. H. Wright, *Jour. Ind. Eng. Chem.*, 1919:

$$n=(n_1-1)\frac{(1-Kt)}{(1-Kt_1)}+1$$

Where n and n_1 are the indices at the temperature t and t_1, and K=modulus of dilatation, which for fixed oils generally = .00076.

The rate of decrease in value of the oils, however, is far greater than the increase in the index of the crystals when raised from room temperature to 70° C. The increase is so slight that it may be ignored, as it involves an error of only one figure in the fourth decimal place at 70° while most of the oils in the writer's collection have a coefficient ranging from .000306 to .000609 per 1°, the average being between .0004 and .0005. The indices of these oils have been measured on a Spencer (Abbé) refractometer at various temperatures from 10° to 70° C. The results were recorded in the form of curves, which are periodically rechecked to insure accuracy. The instrument is accurate to .0003, although it is said to be .0002 (H. S. Simms, *Jour. Ind. and Eng. Chem.*, June, 1921). The fragments (passed through 100-mesh and caught on 120-mesh screens, approximately .3 mm. in diameter) are mounted in an oil whose index at normal room temperatures is higher than any of the indices of the feldspar. The slide is then placed in an electric hot stage (a remodeled biological stage, with an adjustable thermostat) and the temperature raised slowly until the Becké test, using monochromatic light, shows that the crystal and oil have the same index. The temperature of the stage is noted (a Taylor Instrument Company's thermometer standardized against the thermometer of the Spencer Refractometer) and the corresponding value in index read from the curve for that particular oil. Furthermore these results have been checked by using Merwin's dispersion diagram (E. Posnjak and H. E. Merwin, *Jour. Amer. Chem. Soc.*, September, 1922). In this manner the indices of both phases of a perthitic feldspar may be conveniently measured from a single mount.

these are forthcoming the writer cannot offer diagrams which are as accurate as desired.

Kozu and Suzuki[1] report that the indices of a moonstone from Korea ($Or_{61.9}$ $Ab_{32.7}$ $An_{5.4}$) vary among the several specimens at hand and even from place to place within the same crystal. To find zonals in orthoclasic feldspars is to be expected but here the indices may vary as much as .002 between two crystals from the same locality. This indicates some of the difficulties in the way of a satisfactory index of refraction diagram for the potash-soda-lime feldspars.

EXTINCTION ANGLES

Similar remarks apply to values of extinction angles. Here again a peg model undoubtedly suggests two series. The plotting of the data is given in Figure 6.

In Part I (p. 229) it was stated that "as the amount of the sodium component [in orthoclase] increases . . . . the (001) extinction angle changes from zero to about three degrees." These potash-soda feldspars were called monoclinic. Professor A. N. Winchell[2] has called the attention of the writer to this obvious error. The extinction angles of strictly monoclinic minerals measured on the trace of the (010) face in cleavage fragments or sections parallel to (001) must necessarily be zero. However, it may be said that the writer employed the term "monoclinic" as a general distinctive name for the orthoclase-barbierite series as contrasted with the triclinic microcline-albite series. It was thought unwise to introduce a new term. As a matter of fact, the statement that the angle varies from zero to three degrees may mean that the specimens so plotted were mixtures of the two series and hence the term triclinic should be applied instead. If the (001) extinctions remain zero it may be that it is because this specimen is a representative of pure orthoclase-barbierite feldspar. Thus the microscopic determination of the potash-soda series is complicated by (1) the effect on the physical properties by the presence of the lime component, (2) by the presence of nephelite-carnegieite, (3) by the possible dimorphism

[1] S. Kozu and M. Suzuki, "Optical, Chemical and Thermal Properties of Moonstone from Korea," *Sci. Repts. of Tohuko Univ.*, Ser. III, Vol. I (No. 1, 1921), p. 20.

[2] Personal communication, May 28, 1921.

of both end members (minals) and (4) by the probable mixture of these two series.

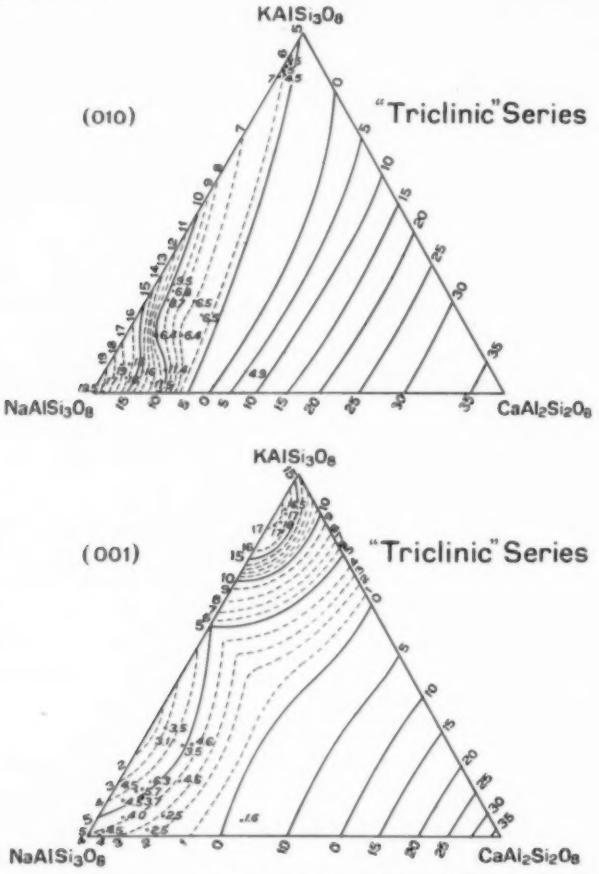

FIG. 6.—Plot of extinction angles for potash-soda-lime feldspars. Upper figure: (010) face. Lower figure: (001), base. Both for "Triclinic" series. The monoclinic series not attempted tentative, subject to revision.

The writer wishes to correct an error in Part I. On page 251 the statement is made that in using the conventional curves for extinction angles of the soda-lime series "it is not possible to deter-

mine the percentage of the lime and potash members with anywhere the same accuracy" as the soda member. "The most satisfactory means . . . . is to consider that the value of the extinction angles gives the percentage of the *soda* component only." From this and the average amount of potash feldspar usually found in plagioclase

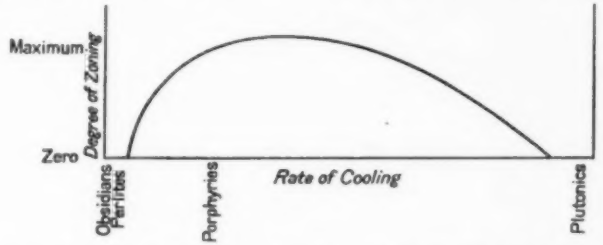

FIG. 7.—Diagram suggesting that porphyritic feldspars are able to possess the maximum amount of zonal structure while feldspars in obsidians, perlites, and plutonics exhibit little or no zonal habit. This diagram is to be considered in a qualitative and not in a quantitative manner.

the other two components can approximately be ascertained. The word "soda" (in italics) is in error. The truth is that extinction angles give the *lime* component more accurately and by assuming 4 to 6 per cent potash feldspar, the amount of the soda component is found by subtracting the sum of these from one hundred.

SUNSTONE AND AVENTURINE FELDSPARS

Viola[1] and Andersen[2] have investigated the aventurine feldspars and the latter reached the conclusion that the included plates of definitely oriented hematite (or magnetite, ilmenite, rutile, etc.) are due to exsolution.[3] This suggests that the original melt could hold a compound of iron in solution while molten but the decrease in solubility of the feldspar for the iron compound with falling temperature caused its separation. Furthermore potassium feldspars are often pink while albite is more frequently white.[4] This may mean

[1] C. Viola, *Zeitschr. f. Kryst.*, XXXIV (1901), 171.

[2] Olaf Andersen, *Amer. Jour. Sci.* (4), XXXIX (1915), 379.

[3] See Alfred Harker, *op. cit.*, p. 257; Judd, *Quar. Jour. Geol. Soc.*, XLI (1885), 374–89; J. H. L. Vogt, *ibid.*, LXV (1909).

[4] "Flesh-colored albite occurs as well as flesh-colored orthoclase."—Iddings, *Igneous Rocks*, Vol. II, p. 46.

that potash feldspar melts can absorb or have a selective ability to dissolve iron-bearing minerals. Such a theory would explain the colorization of orthoclase and microcline in granites, syenites, etc. In contrast to this idea is the light that is cast when the ferric feldspars are considered. As long as feldspars are considered as salts of

TABLE V

ORTHOCLASE, MADAGASCAR

	1	2	3a	3b
SiO_2	64.19	63.99	64.76	64.72
Al_2O_3	16.62	18.02	17.98	17.97
Fe_2O_3	2.88	0.97	1.18	1.20
FeO	0.18	0.00	0.09	0.09
MgO	.....	.....	0.08	0.09
CaO	.....	0.50	0.16	0.10
BaO	n.d.	0.06	n.d.	n.d.
Na_2O	0.34	1.86	1.07	0.94
K_2O	15.81	14.32	15.39	15.18
H_2O	.....	0.51	.20	0.19
Total	100.02	100.23	100.91	100.48
$KFeSi_3O_8$	11.02	5.05	4.54	4.61
$KAlSi_3O_8$	82.50	81.37	86.63	85.45
$NaAlSi_3O_8$	2.89	10.74	9.06	7.96
$CaAl_2Si_4O_8$	.....	2.48	0.79	.49
$BaAl_2Si_4O_8$	.....	0.15	.....	.....
Total	96.41	100.76	101.02	98.51
Excess SiO_2	1.92	.....	.....	.....
Excess Al_2O_3	1.32	.....	.....	.....
	99.65	.....	.....	.....

1. Lacroix, *Min. de la France*, XXIX (1913). Boiteau, analyst. Deep lemon yellow. (Kindness of Henry S. Washington.)

2. Lacroix, *Min. de Madagascar*, I (1922), 560. Raoult, analyst. Nearly colorless. (Kindness of Henry S. Washington.)

3. Material from Ward's Natural Science Establishment. Madagascar Mining Co. Analysis by H. B. Croasdale, Fraser Laboratories, New York City.

ortho- and trisilicic acids the non-replaceability of the aluminum by ferric iron is indeed striking. The apparent absence of such feldspars is more understandable if these minerals are alumino-silicates. However, $KFeSi_3O_8$ has been synthesized by Hautefeuille and Perrey[1]

[1] P. Hautefeuille and A. Perrey, *Compt. Rendu.* (1888), 107, 1150, and *Zeitschr. f. Kryst.* XVIII (1891), 329.

who recorded its physical properties. This ferric feldspar is, however, unstable and it is a very reasonable supposition that much of the hematite in aventurine feldspars is derived from the decomposition of $KFeSi_3O_8$. As this is a potash feldspar it is perhaps to be expected that it would occur in orthoclasic or microclinic feldspars. The gem orthoclase from Madagascar is perhaps unique, as Wherry notes. The writer's suggestion is that perhaps it contains some undecomposed $KFeSi_3O_8$. The following analyses of this feldspar from Madagascar show, when recast, the probable presence of this potash-ferric component.

The question arises: Has the compound $KFeSi_3O_8$ any bearing on the color of amazonstones?

While the work of the Geophysical Laboratory on the $MgO-Al_2O_3-SiO_2$ system shows no compound $MgAl_2Si_2O_8$, the writer asks whether or not the existence of a magnesium feldspar, stable only in small quantities in the presence of other feldspars, would not explain the occurrence of MgO in many of the analyses?

BARIUM FELDSPARS

In view of Eskola's[1] recent paper it is not necessary that a complete discussion of the synthesis of strontium and barium feldspars be given here. It is sufficient that a summary of the present status of these minerals and their relationships to the more common feldspars be recorded.

Descloizeaux[2] found that some of the lime in plagioclase can be replaced by barium without changing its triclinic character. The work of Ginsberg[3] on the $CaAl_2Si_2O_8$–$BaAl_2Si_2O_8$ system indicates that anorthite will dissolve a limited amount of the barium feldspar forming a solid solution, and likewise barium feldspar will form a restricted range of solid solutions with anorthite. On this basis we can conclude that the system is a eutectiferous one with limited solubility.

[1] Pentti Eskola, "Silicates of Strontium and Barium," *Amer. Jour. Sci.* (5), IV (1922), 331–75, especially pp. 364–67.

[2] A. Descloizeaux, *Tscherm. Min. Petro. Mitt.*, VII (1877), 99.

[3] A. S. Ginsberg, *Ann. de l'Inst. Polytech. Pierre le Grand à Pétrograde*, XXIII (1915).

Sjogren[1] and Strandmark[2] studied celsian, the latter proving that celsian and orthoclase form an isomorphous solid solution series called hyalophane.

TABLE VI

CASSINITE, BLUE HILL, DELAWARE COUNTY, PENNSYLVANIA

	1	2	3	4
SiO_2	62.60	62.95	62.92	62.91
Al_2O_3	19.97	19.82	20.25	20.28
Fe_2O_3	0.31	0.28	0.20	0.22
FeO			0.09	0.09
MgO			0.10	0.11
CaO	0.19	0.25	0.52	0.45
Na_2O	4.31	4.01	3.58	4.03
K_2O	8.95	8.57	9.08	8.86
H_2O			0.15	0.16
SO_3			n.d.	0.21
BaO	3.71	3.95	2.78	2.64
SrO	n.d.	n.d.	0.02*	0.02*
Total	100.04	99.83	99.69	99.98
	1 and 2		3 and 4	
Orthoclase	53.30		56.05	
Albite	36.01		34.30	
Anorthite	1.13		2.55	
Celsian	9.56		7.00	
Sr-Feldspar			0.10	
Total	100.00		100.00	

* Approximate, spectroscopic determination.

Analyses 1 and 2: Penfield and Sperry, *Amer. Jour. Sci.* (3), XXXVI (1888), 324. See Dana, *System of Mineralogy*, p. 319.

Analyses 3 and 4: Made for the writer by H. B. Croasdale of the Fraser Laboratories, New York City.

Penfield and Sperry[3] have described a barium-bearing perthitic feldspar from Blue Hill, Delaware County, Pennsylvania.[4] Their

[1] Hj. Sjogren, *Geol. Fören. Förh.*, XVII (1895), 578.

[2] J. F. Strandmark, *Geol. Fören. Förh.*, XXV (1903), 289; XXVI (1903), 97; *Zeitschr. f. Kryst. Min.*, XLIII (1907), 89.

[3] S. L. Penfield and Sperry, *Amer. Jour. Sci.* (3), XXXVI (1888), 324.

[4] Dana, *A System of Mineralogy*, p. 319: "A dull bluish-green subtransparent kind, of an aventurine character, from Blue Hill, 2 miles north of Media, Pa., *cassinite.*" P. 322: "Cassinite of Lea from Blue Hill, Delaware Co., Penn.; shown by Penfield to be a monoclinic feldspar (extinction on $b = \pm 6°$) with albite running through it in thin tapering plates parallel to the orthopinacoid. The analysis corresponds to 35 p. c. albite, 51 p. c. orthoclase, and 13 p. c. of $BaAl_2Si_4O_{12}$." This formula is incorrect. It should be $BaAl_2Si_4O_8$.

analyses are given in the following tables, together with analyses made for the writer from material supplied by Dr. Samuel G. Gordon of the Philadelphia Academy of Science. As it agrees with the description of the original material there is but little doubt that it is a good representative. Under the microscope it is at once seen to be an intergrowth of a barium-bearing orthoclasic feldspar, hyalophane, and a potash rich albite. Quantitative microscopic measurements[1] resulted as follows:

Phase	Units Measured (Areas)	Spec. Gr.	Product	Reduced to 100
Hyalophane	17,300	2.555	44,200	68.65
Plagioclase	7,690	2.6225	20,180	31.35

The distribution of the four components as obtained from recasting Penfield and Sperry's analyses into the two phases must be something like this:

Phase	Per Cent	Orthoclase	Albite	Anorthite	Celsian
Potash	68.65	52.20	7.76	0.13	8.56
Soda	31.35	1.10	28.25	1.00	1.00
Total	100.00	53.30	36.01	1.13	9.56

This grouping agrees well with the extinction angles:

Potash phase.....(010)..... 18°
Soda phase.....(010)..... 6°

and the specific gravity: 2.692.

The results of recasting Croasdale's analyses can be arranged in a similar manner as follows:

Phase	Per Cent	Orthoclase	Albite	Anorthite	Celsian
Potash	68.65	54.46	7.15	.55	6.50
Soda	31.35	1.59	27.15	2.00	.50
Total	100.00	56.05	34.30	2.55	7.00

[1] See Part I, pp. 248–59, for an outline of the method used.

Indices of refraction:

Potash phase	α	1.523
	β	1.527
	γ	1.529
Soda phase	α	1.528
	β	1.533
	γ	1.535

Extinction angles:

Potash phase	(001)	1.5°–2°
	(010)	6.° –8°
Soda phase	(001)	4.°
	(010)	18.°

We can draw the conclusion that celsian is not isomorphous with any of the plagioclase feldspars, including albite.

STRONTIUM FELDSPARS

Eskola says: "It was . . . . found that the strontium feldspar is, in its optical properties, exactly like the calcium feldspar. . . . . It is . . . . probable that the strontium feldspar forms a complete series of solid solutions with anorthite."[1] He does not state its relation to orthoclase but it is reasonable to expect that it does not form solid solutions with it to any extent. As an illustration of barium and strontium bearing feldspars the following analysis of an albite from Seiland, Norway, is introduced.

TABLE VII

ALBITE FROM SEILAND, NORWAY

Analysis calculated to 100

	Percentage	Recast	
SiO_2	66.87	.....	.....
Al_2O_3	20.55	.....	.....
CaO	1.04	Albite	87.11
BaO	.11	Orthoclase or microcline	6.20
SrO	.11	Anorthite	5.16
Na_2O	10.27	Celsian	0.26
K_2O	1.05	Sr-Feldspar	0.35
Total	100.00	.....	99.08 per cent

[1] P. Eskola, "Silicates of Strontium and Barium," *Amer. Jour. Sci.* (5), IV (1922), p. 367.

TABLE VIII

TABULAR SUMMARY

Minals

Hexagonal	Monoclinic	Formula	Triclinic
.....	Orthoclase	$KAlSi_3O_8$	Microcline[1]
.....	"Barbierite"	$NaAlSi_3O_8$	Albite
.....	.....	$CaAl_2Si_2O_8$	Anorthite
.....	Celsian	$BaAl_2Si_2O_8$	.....
.....	.....	$Na_2Al_2Si_2O_8$	Carnegieite[2]
Nephelite	.....	$NaAlSiO_4$	.....
.....	.....	$SrAl_2Si_2O_8$	Strontium Feld

Series

Minals	Solid Solutions	Intergrowths
Orthoclase-Albite }	Anorthoclase[3]	Perthite[4]
Microcline-Albite }		
	Transitional crypto-microperthite	
Albite-Anorthite.....	Plagioclase[5]	.....
Orthoclase-Anorthite }	.....	Oranite[6]
Microcline-Anorthite }		
Carnegieite-Anorthite.....	Anemousite[7]	.....
Orthoclase-Celsian.....	Hyalophane[8]	.....
Plagioclase-Hyalophane.....	.....	Cassinite[9]
Sr-Feldspar-Anorthite.....	No Name	.....
Sr-Feldspar-Orthoclase }	.....	No Name
Sr-Feldspar-Microcline }		
Sr-Feldspar-Albite.....	No Name	.....

[1] Microcline. Breithaupt, *Jour. Ch. Ph.*, LX, p. 324. "Triclinic potash feldspar."

[2] Carnegieite. H. S. Washington, *Jour. Geol.*, XVI (1908), 10; H. S. Washington and F. E. Wright, *Amer. Jour. Sci.* (4), XXVI (1908), 187, and XXIX (1910), 52–70, also XXXIV (1912), 555.

[3] Anorthoclase. Rosenbusch, 1886, *Mic. Phys.*, 550. A triclinic soda-potash feldspar resembling orthoclase.

[4] Perthite. Thomsen, 1832, *Shep. Min.* (1), 232. Interlamination of orthoclase and albite. First considered a variety of orthoclase.

[5] Plagioclase. Breithaupt, *Breit. Handb.*, III, 492, General term including several triclinic feldspars.

[6] Oranite. H. L. Alling, *Jour. Geol.*, XXIX (1921), 235. Intergrowth of either orthoclase or microcline and anorthite.

[7] Anemousite. See references under Carnegieite.

[8] Hyalophane. Waltershausen, *Progg. Ann.*, XCIV, 134.

[9] Cassinite. Lea, 1866, *Acad. Nat. Sci. Proc.*, 110. A variety of orthoclase containing barium. Extended by Alling to mean intergrowths of hyalophane and plagioclase. 1923.

CONCLUSIONS

To the conclusions reached in Part I, to which the reader is referred, the following are to be added:

1. The degree to which the potash-soda feldspars undercool, depending upon their origin, renders it impossible to construct a

single thermal-diagram to illustrate the crystallization of the system. Consequently a *series* of diagrams, one for each mode of origin, is necessary. (Fig. 1.)

2. The proof of the dimorphism of $KAlSi_3O_8$ and $NaAlSi_3O_8$ is exceedingly difficult to obtain. The "peg models" of the specific gravities, indices of refraction and extinction angles, suggest two series, one the orthoclase-barbierite and the other the microcline-albite series. No entirely satisfactory series of diagrams that show the dimorphism of both components can be made at the present time.

3. The existence of nephelite in solid solution in feldspars is more common than is supposed. When present it profoundly affects the physical properties, so that determination by microscopic means alone is very uncertain. It may be that the specimen from which barbierite was named is a nephelite-bearing albite.

4. Granting dimorphism, many rapidly cooled feldspars, such as sanidines and orthoclases, possibly may be mixtures of two distinct series: the so-called "monoclinic" series and the "triclinic" feldspars. This sometimes renders determination a difficult matter.

5. Twinning is caused in part by pressure. It may be caused by stress set up by the change in volume accompanying inversion. "Scotch-plaid" twinning is not a reliable criterion for microcline. The writer agrees with Hawes that plagioclase is not always striated, and would put the reader on his guard.

6. The decomposition of the unstable ferric feldspar, $KFeSi_3O_8$, may well account for pink microclines and other aventurine feldspars.

7. Zonal-grown crystals are perfectly normal in rocks cooled at the proper rate. Too rapid cooling prevents zonals while slow cooling allows them to become homogeneous through reaction between themselves and the still unfrozen liquid of the magma.

8. The main contributions are the diagrams giving the specific gravities, indices of refraction, and the extinction angles of the potash-soda-lime feldspars.

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The writer is under obligation to many for helpful suggestions, constructive criticism, assistance, and encouragement. Among these he takes pleasure in expressing his indebtedness to Professors

Kemp, Berkey, Campbell, Colony, and Kendall, of Columbia University; Professor A. N. Winchell, of the University of Wisconsin; Professor Albert Johannsen, of the University of Chicago; Professor William S. Bayley, of the University of Illinois; and to Dr. Henry S. Washington and Dr. Pentti Eskola, of the Carnegie Institution of Washington. Dr. S. Kozu, of Tohoku University, Sendai, Japan; Dr. Olaf Andersen, of the Norwegian Geological Survey; Dr. Edgar T. Wherry, of Washington; Dr. Samuel G. Gordon, of the Philadelphia Academy of Science; Mr. George L. English and Dr. A. C. Hawkins, of Ward's Natural Science Establishment, Rochester; and Professor Henry E. Lawrence, of the Department of Physics of the University of Rochester, have also rendered valuable assistance.

ERRATA

Page 285, ninth line from bottom. For "*i* . . . . monoclinictr⇄icilinic . . . ." read "*monoclinic⇄triclinic*. . . . ."

Bottom of page 290, for "$KAlSi_2O_6+SiO_2 \leftrightharpoons KAlSi_3O_8$" read: "$KAlSi_2O_6+SiO_2 \leftrightharpoons KAlSi_3O_8$"

Title of Fig. 3, page 291, for "$KAlSi_2O_8$" read "$KAlSi_3O_8$."

Footnotes on page 292 (facing Plate I) belong on page 305.

Page 298 (facing Plate II) Feldspar "I," for "Granite" read "*Oranite*."

For footnotes on page 305 *see* page 292.

SIGNIFICANT AMELIORATIONS OF PRESENT ARCTIC CLIMATES

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In an article in a recent number of this *Journal*[1] it was found by comparisons of oceanic with terrestrial climates between mid-latitudes and the poles that the present effect of the ocean on climate in those latitudes is cooling rather than warming. It was found further that theoretical considerations lead to the same conclusion. Thus these inquiries disclosed the untenability of the veteran theory that the ancient mild climates of high latitudes are assignable to extension of the ocean in itself alone considered. At the same time, the inquiry made it evident that the sea is a potent climatic influence. This is largely due to its exceptional capacity for storing heat and the facility with which it transfers heat because of its mobility. The data for comparison were so ample and convincing that it was not felt necessary to dwell on the details of the most striking case of climatic amelioration in high latitudes now available for study. This was reserved for special discussion in the present article, because it is singularly well fitted to reveal the really effective sources of such climatic ameliorations. This most instructive case is found at the head of Baffin Bay, in a *land-girt* region on the *west* side of the oceanic thoroughfare between the Atlantic Ocean and the Polar Sea. Because of the relative mildness of its climate and the abundance of its food supplies, this region has been the home of the Arctic Highlanders, a tribe of healthy, vigorous and competent Eskimos, for an unknown period. Theirs is the most northerly permanent settlement of the world at the present time. This habitable land is isolated on all sides by tracts so inhospitable that they are not permanently inhabited by man. It is an oasis in the frigid desert of the north. Its significance stands out when its land-girt

[1] T. C. Chamberlin, "A Veteran Climatic Fallacy," *Jour. of Geol.*, Vol. XXXI (1923), No. 3, pp. 179–91.

situation and its position on the west side of the Atlantic drift are compared with the sea-girt situations of Spitzbergen and Franz Joseph Land in practically the same latitude on the warm side of the Atlantic drift. These islands have no permanent human inhabitants.

South of the land of the Arctic Highlanders and separated from it by an inhospitable tract of two hundred miles, the dreaded Melville Bay, lies a coastal belt of relative mildness occupied by the Danish Colony of West Greenland. While this lies mainly between 63° and 73° N. Lat., scattered settlements reach nearly to the southern point of Greenland, and a single settlement of Eskimos, Angmagssalik, is more or less permanently maintained on the southeast coast. Though this is itself quite isolated, it seems, in a sense, to connect the West Greenland Colony with the settlements on Iceland. The real effect of this feeble connection, however, is rather to relate the climate of Iceland to the climatic mildness in Baffin Bay than to suggest that the latter is a normal part of influences referable to the "Gulf Stream." The district occupied by the Danish Colony of Greenland is a true factor in the singular climatic amelioration on the east coast of Baffin Bay, and will be treated as the more southerly and larger twin of the little oasis at the head of the bay. It is not, however, milder than some other tracts of its own latitude. While the mildness of both these tracts is very notable for their situation and latitude, it is to be understood that these are *Arctic* climates and much more severe than those singularly genial climates implied by the fossils of several geologic stages.

THE SIGNIFICANT FEATURES OF THE GENERAL SITUATION

The most remarkable feature of these districts of climatic amelioration is that they lie northward from the northwest angle of the Atlantic Ocean and reach within 12° of the North Pole. It is especially to be noted that they are not in the great oceanic sweep of the warm Atlantic drift into the Polar Sea. They bear the aspect of offshoots or outliers from *the coldest corner of the Atlantic*. This is emphasized by the further fact that between them and the main warm Atlantic drift there runs the greatest of the Arctic outlets, carrying southward a compact stream of ice-floes from the border

of the polar ice-field. It is therefore important to enter into some detail respecting the essential features of this singular situation.

A broad sea-arm branches off from the northwestern angle of the Atlantic and gradually narrows northwardly until it forms Davis Strait, although even here it has a width of 200 miles (see map, Fig. 1). This narrowing is due to a submerged ridge crossing the sea-arm at this point and linking Greenland to Baffin Land. It is a part of an intercontinental ridge to be described later. Beyond this ridge the sea-arm broadens again and constitutes Baffin Bay, which attains a maximum breadth of about 480 miles, a depth at several places of over 1,000 meters, and stretches onward to about 78° N. Lat. As the bay approaches this high latitude, the lands on the east and west close about it and its bottom shelves up into relative shallowness. A rather narrow channel, Smith Sound, leads on to the northward and connects, through Kennedy and Robson channels, with the Polar Sea. The tide enters the poleward mouth from the north, and the drift of the ice in these channels is southward into the head of Baffin Bay, but this drift is pressed to the right by rotation and keeps mainly on the western side of the bay. Farther south on this western side, Lancaster and Jones sounds join Baffin Bay nearly opposite Melville Bay, into which they project their cold waters. Both these sounds lead back through other narrow channels westward and northwestward to the Polar Sea and are fed by its icy waters, which press into them as though they were outlets. With exceptions of this limited kind, Baffin Bay is land girt. The great island, Greenland, confines it on the east and north; the islands of the American Arctic Archipelago border it on the west. The whole sea-arm takes the form of a long inlet into the broken northeast angle of North America. From its mouth to the head of Baffin Bay, this inlet has a length of about 1,500 miles. Looked at comprehensively, the region is more largely land than sea, although distinctly a combination of the two.

Relations to ice-bearing currents.—The East Greenland ice-bearing current is the greatest of all avenues of discharge of ice-floes and melt-waters from the Polar Basin. Apparently, also, it is the main line of ultimate discharge of the land waters that flow toward the pole. The investigations of Nansen and his colleagues seem to

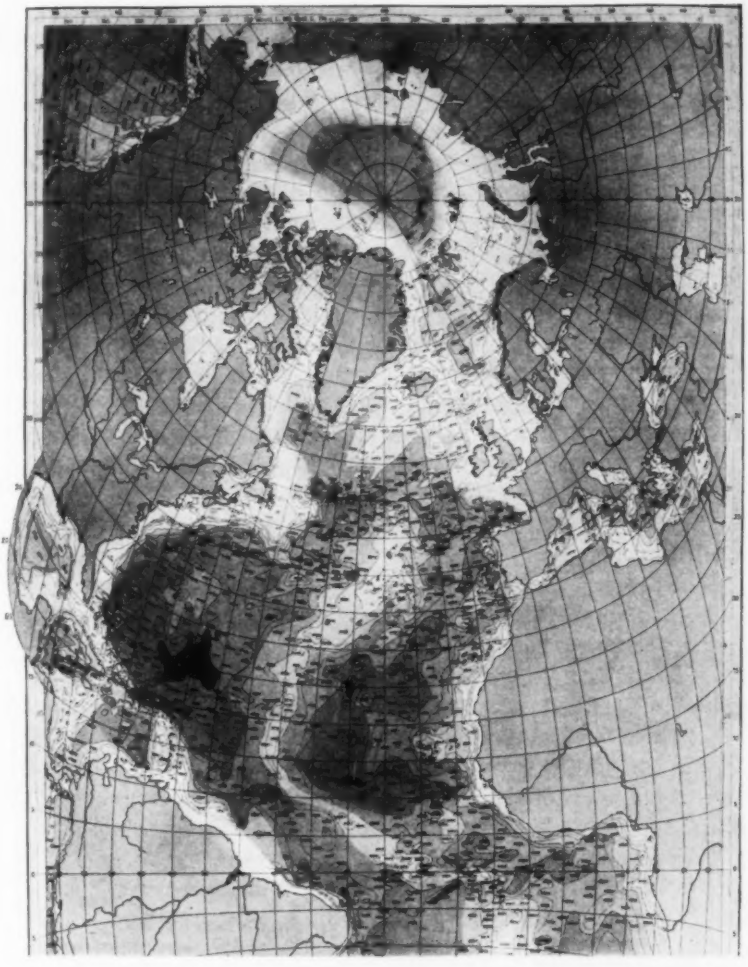

FIG. 1.—Photographic reduction of map of the North Atlantic Ocean issued by the Institut für Meereskunde der Universität Berlin (1912). Original in colors. Oceanic depth in meters: contours = −100, −1,000, −2,000, −3,000 −4,000 −5,000, −6.000 −7,000, −8,000, over 8,000.

show that the north Eurasian rivers find their ultimate exit from the Polar Basin through it. The procession of ice-floes in the season favorable to it is very compact, and usually hugs the coast of Greenland as far south as Cape Farewell, about which it wraps closely—unless forced off by winds—and, swinging to the northward, crosses the open mouth of Davis Strait and joins a similar ice-bearing current coming from the northward along the coast of Baffin Land. This latter carries ice-floes from the inlets that join Baffin Bay at the north and on its western side, as already stated, together with the local ice of the bay, and the icebergs discharged into it from the Greenland glaciers. These usually move in stately processions southwestwardly across the bay. This Baffin Land current and the great East Greenland current join at the south to form the Labrador current, which is felt as a pronounced cooling influence as far south as the coast of Maine, and less markedly beyond.

It thus appears that the climatic oases under study lie in the fork between two great streams of polar ice-floes and icebergs, while beyond lies the polar ice-field itself.

It is not necessary to urge that the relative mildness under study is due to warm waters coming from somewhere and reaching these oases somehow. That scarcely requires discussion. It appears that such warm waters could ordinarily reach these areas of climatic amelioration only by passing *under* the currents that discharge the polar ice-floes. It does not seriously affect the general truth of this that there may be occasional or seasonal conditions under which warm currents may reach the Danish Colony as surface currents along the coast of Greenland as represented on some charts. I know of no claim that even these reach the northern oasis.

The icy barrier between the northern and the southern oases.—The inhospitable tract which separates the two ameliorated areas apparently owes its origin to the projection into and across Melville Bay of streams of cold waters from the Polar Sea through Lancaster and Jones sounds, which join Baffin Bay on the west opposite Melville Bay (see map, Fig. 1). As already noted, these sounds reach back through connecting channels to the great ice-fields of the Polar Sea, and their mouths in that direction are persistently choked by ice-floes driven into them from the west and north. It is the persis-

tent ice blockade thus formed which has rendered futile so many attempts to force a ship through what would be—but for the ice—a convenient "Northwest passage," though the attempt has been bravely renewed again and again for two centuries. As these polar waters, projected across the Baffin tract, curve about in Melville Bay and begin to move south, they veer to the right, because of the earth's rotation, and so follow the west side of Baffin Bay, leaving opportunity for the rise of warm waters on the east side, where not prevented by the intrusion of these polar streams. Like the other polar streams, these that occupy Melville Bay are surficial; the warm currents that give amelioration to the oasis north of it *pass under it.*

The degree of amelioration of the northern oasis.—Among the familiar evidences of amelioration, it may be noted that the tract north of the inhospitable Melville Bay long ago acquired from explorers the title, "The North Open Water." There is little doubt that the striking nature and persistence of this open water, so far north, gave rise to the dream of an "open polar sea," which for a long time was confidently entertained by some of the early explorers. The freshest testimony as to the openness of this region in winter, from a scientific source, is given incidentally in the discussion of icebergs by Lauge Koch in a recent number of this *Journal.*[1] Koch defines his second class of icebergs as those which break off from glaciers "on an open coast where no sea ice is formed in winter, so that there is no hindrance to the formation of bergs. Of this type are the glaciers of Cape Alexander, in 78° North lat."[2] Cape Alexander lies near the northern edge of the oasis under discussion. Near by it on the north is Etah, an Eskimo settlement that has become widely known from the part it has played in Arctic exploration.

Admiral Peary speaks of this region as "one of the most interesting of all Arctic localities"; and also as "a little oasis amid a wilderness of ice and snow. . . . . Here, in striking contrast to the surrounding country, is animal and vegetable life in plenty,

[1] L. G. Koch, "Some New Features in the Physiography and Geology of Greenland," *Jour. of Geol.*, Vol. XXXI (1923), No. 1, pp. 42–65.

[2] *Ibid.*, p. 53.

and in the course of the last hundred years some half a dozen Arctic expeditions have wintered here."[1]

The singular abundance of the lower life of this region has been the subject of so much surprised comment and vivid description by Arctic explorers and scientific visitors for the last century that there is no need to go into much detail here. There is a well-rounded fauna which embraces long chains of species dependent on one another for support. This implies permanence and steadiness of evolution. These biologic chains reach from great predaceous sea mammals, birds and man, down through many intermediate types to minute orders of sea or land life. It is to be noted that no large part of the life in this region consists of *outre* forms dependent on scant supplies of food and on protection by isolation, as in the case of the Antarctic penguins and like types. The fauna here embraces multitudes of migrant forms of bird life of wide-ranging types which congregate here to feed and to nest. Such large assemblages are the best of evidence of climatic geniality and richness of feeding ground. There is also a large non-migrant element which must of course find food during the winter, and this sufficiency of winter food is in itself an unequivocal form of testimony to the hospitality of the climate.

The life of the tract occupied by the Danish Colony has been quite fully studied, and is set forth in Rink's "Greenland" and in many later papers. It will suffice for this discussion to refer to Seward's recent statement—quoted in the review of his book on *A Summer in Greenland* in a recent number of this *Journal*[2]—to the effect that while not a flowering plant is known in the Antarctic region nearer the pole than 62° S. Lat., more than 400 species of flowering plants grow in Greenland above the corresponding north latitude.

However, notwithstanding this abundance of life, it is to be clearly understood that the present Greenland oases are merely remarkable ameliorations of *Arctic* climates. They are not climates of the warm temperate or subtropical sort, such as are implied by

[1] *The North Pole* (1910), p. 36.

[2] A. C. Seward, *A Summer in Greenland*. Review by T. C. Chamberlin, *Jour. of Geol.*, Vol. XXXI (1923), No. 3, pp. 253–55.

the fossil faunas and floras of these and other high latitudes in certain periods of the Paleozoic, Mesozoic, and Cenozoic eras. The present polar climates are really of the glacial order, and the present epoch is, in my view, to be regarded climatically as a part of the Pleistocene glacial period. The present stage seems to belong to the degree of severity usually called interglacial, though we hope the present stage is to prove *terminal* rather than really *inter*glacial.

THE MORE REMOTE SOURCE OF THE AMELIORATION

It has been indicated already that the mildness under study is due to warm waters that have found their way to these localities notwithstanding their location off the northwest corner of the Atlantic in a region of glaciers and in spite of the polar ice-streams that predominate at the surface and cross the line of connection with the warm regions of the Atlantic. There is no ground to question the immediate agency of relatively warm waters coming to the surface in the ameliorated tracts; our problem lies wholly in the localization of these emergences of warm water and the ulterior causes that actuated them. In the main it is a question of the flow or creep of warm rather saline waters under colder ice-bearing waters which are lighter because less saline. Concretely, the crux of our problem lies in explaining an underflow or undercreep of warm Atlantic waters *to the northwestern corner* of the Atlantic, and sending thence an offshoot 1,500 miles to the northward. Still more specific is the question why so seemingly anomalous a current should be more effective at the head of Baffin Bay than is the broad "Gulf Stream" or "Atlantic Drift" on Spitzbergen or on Franz Joseph Land.

Two factors in the answer have probably already suggested themselves:

1. *Carrying heat under cover.*—The very fact that the warm waters of the ameliorated tracts of Baffin Bay can only, as a rule, reach the place of their appearance at the surface as *undercurrents* suggests that they lost less of the heat they gained in low latitudes on the way than they would if they had flowed at the surface for so great a distance. This factor of transportation under cover will, I think, appear to be one of great importance in some of its

wider applications to be discussed later. It is not that there is great importance in explaining this unique case, but the principle of carrying heat under cover has far-reaching applications in the greater climatic problems of geologic history. Even in this case, as will appear a little later, much more than usual emphasis will be laid on the function of the middle layer, the layer under cover, in bearing warmth to the high latitudes and in promoting that particular phase of oceanic circulation of which the warm undercurrent of Baffin Bay is regarded as an offshoot.[1]

2. *Confinement rather than deployment.*—A second factor that seems to conduce to the special mildness in the areas under study is the degree to which the waters of the warm currents in the Baffin inlet are prevented from spreading and increasing their contact surfaces and thus losing heat and suffering mixture by this increased contact. Baffin Bay occupies a rather narrow, deep trough between lands on either hand. It converges at its head, where the northern oasis lies, and there the warm current seems to be concentrated and

[1] To forestall misunderstanding as to the extent and completeness of the overriding lighter ice-bearing currents near the mouth of Baffin Bay, it is to be recognized that on some charts and in some descriptions a warm surface current is represented as flowing from the Erminger current south of Iceland around the southern point of Greenland and along the east side of Davis Strait into Baffin Bay, but this is to be accepted only in a qualified sense, for the connection of the East Greenland stream of polar ice-floes with the Labrador current and the currents that flow down the west side of Baffin Bay is not only well established but is recognized as a normal and dominant feature of the general system of interchange between the polar and the Atlantic circulations. As I saw this great ice-stream in July, 1894, in what I understand to be its normal state for that season, its complete continuity and its dominance were very impressive, and there could be no question as to the complete exclusion of any warm cross-current at the surface. But the seasons bring variations in the relative strength of the currents, and special winds cause diversions. Some of these special influences may open the way for temporary warm currents at the surface along the west coast of Greenland. Tropical wood, presumably from the West Indies or the tropical coasts of the American mainland, is sometimes found on the coast of the Danish Colony, and this seems at first thought necessarily to imply the continuity of a warm current from the south at the surface, but the evidence is less rigorous than it seems, for floating matter may be shifted from one current to an adjacent one of different type and destination by transverse winds. Though it has seemed necessary to recognize this testimony to an assigned surface current from the warm Atlantic waters into Baffin Bay, it is quite certain that the mild climates of the Danish Colony, and especially of the land of the Arctic Highlanders, are not dependent on breaks in the continuity and dominance of the main ice-streams that serve as outlets of the Polar Sea.

pressed to the surface. This is in contrast to the situations in which Spitzbergen and Franz Joseph Land lie. There the warm currents from the south are not only permitted to spread, but the opening of the connecting tract into the Polar Sea seems to require this. Though these islands stand in the broad avenue through which the "Gulf Stream" or the "Atlantic Drift" flows toward the Polar Sea, they necessarily suffer from the spreading of the warm waters over a broad surface and their consequent cooling. Though these waters appreciably warm the tract traversed, the effect is insufficient to maintain such a persistent hospitality and such prolific life as does the unique little tract at the head of Baffin Bay. This is a striking verification of one of the theoretical conclusions offered in the last article.[1]

The remaining problem.—But giving to these two factors all that is due them, the anomaly of a climatic oasis within 850 miles of the North Pole and on the cold side of the oceanic thoroughfare between the Atlantic and the Polar Sea is not yet adequately explained. There is little ground to expect to reach any such explanation without analyzing the modes of oceanic exchange between the producing sources of warm water and of cold water, respectively, which involves that of saline water, on the one hand, and fresh water, on the other. This requires attention to the configuration of the Polar and Atlantic basins in which the opposite kinds of water are generated, as also of the intervening thoroughfare through which the exchange of these waters takes place. It is a step of some consequence to recognize definitely that there are two dominant areas of generation and a connecting tract between them. The connecting tract is often rather loosely regarded as a part of the Atlantic Basin, or else as a part of the Polar Basin, but it is better to regard it as neither. Functionally, it is a connecting avenue *defined at either end by partially submerged intercontinental ridges; these ridges serve at once as dams and as weirs.* Between the ridge-dams and weirs at either end there is an uneven tract occupied by basins, shallows, and islands. The parts of this tract that most concern us in this discussion are the Norwegian and Berentz seas,

[1] "A Veteran Climatic Fallacy," *Jour. of Geol.*, Vol. XXXI (Feb.-Mar., 1923), pp. 179–91.

and the deeps, shallows, and islands connected with them, though the region to the east as far as the New Siberian Islands and beyond is involved. It is not necessary, however, to dwell on the intricate details of circulation in this connecting tract, except so far as it affected the interchange between the generating basins on either end, for the gist of our present problem centers in the Polar Basin, where cold waters are generated, and in the Atlantic Basin, where warm waters are generated. Let us, therefore, look upon the connecting tract merely as an oceanic thoroughfare with ridge-dams and weirs at either end. There is so little exchange through the channels of the American Archipelago and through Behring Strait that these may be neglected here.

THE INTERCONTINENTAL RIDGES

The Southern Intercontinental Ridge.—The more southerly of the partially submerged ridges that connect Eurasia and North America has for its best-known section the Wyville-Thompson Ridge, but this is merely the most exploited sag in a much greater feature. The ridge is continuous from the Wyville-Thompson sag southeastward through the British Isles to the European continent, and northwestward through the Faroes, Iceland, Greenland, Davis Strait, and Baffin Land to the American continent. This Southern Intercontinental Ridge has, at present, more critical climatic bearings on the Atlantic-Polar exchange than the Northern Ridge, because its lowest notches have less depth and give a shallower weir or a higher dam as one chooses to look at it. It is, of course, to be kept in mind that the exchanging waters pour over this weir in *both* directions as they do at the Straits of Gibraltar, the Dardanelles, and many other such weirs. The greatest depth of water over this Southern Ridge thus far disclosed by soundings is 314 fathoms, or about 600 meters, but the exploration is as yet incomplete.

The Northern Intercontinental Ridge.—Separated from the Southern Intercontinental Ridge by about 20° latitude is the Northern Intercontinental Ridge, connecting the northerly border of the Eurasian continent, by way of Franz Joseph Land, Spitzbergen, North Greenland, and Grinnell Land, with the northern islands of the American Archipelago and the northern border of the American

continent. This ridge lies near the edge of the two continents and not far back from the abyssal portion of the Polar Basin. The bordering flat between the ridge and the basin has about the usual width, depth, and aspect of a continental shelf. The deepest submerged notch in this ridge seems to lie between Spitzbergen and Greenland, but it has not as yet been positively defined by soundings. The difference between the abyssal waters of the Norwegian Sea and those of the Polar Basin, however, make the existence of a defining weir of this kind practically certain, and fix the maximum depth of water over it at about 3,000 meters. As well brought out by Nansen and others, these two ridges, acting as weirs, determine the upper boundary of the abyssal waters in the Polar Basin and in the Norwegian Basin, respectively, and through this determination they indirectly fix the depths attained by the currents or layers of water formed by the circulation above the abyssal waters.

So far as known, the inlets through the American Archipelago into Baffin Bay and Hudson Bay are too shallow to be occupied by any but the upper currents flowing out of the Polar Basin; this statement may, however, be found to need revision. It is wise to bear in mind that canyon-like channels across barriers like these partially submerged ridges that serve as weirs may easily excape the sounding-lead, especially when soundings are few. And more than that, such canyons may once have existed but were filled afterward and may now be quite indetectable. The shallow Behring Strait plays only a small part relatively in the exchanges between high and low latitude and need not be considered in this discussion.

One of the notable effects of the Southern Intercontinental Ridge is that it holds the surface of the cold saline abyssal waters of the Polar Basin a thousand meters or more above the surface of similar abyssal water in the mid-Atlantic as now determined. As the less dense layers of water developed above these heaviest abyssal waters yield to them, and must conform to them in both basins, this great difference is a radical feature. It implies that in seeking an interpretation we should proceed on the assumption that the superabyssal water-strata of the mid-Atlantic, taken together, are much thicker than the corresponding layers of the Polar Basin. This greater depth is well established for the tracts of the mid-Atlantic,

whence the warmer upper and middle layers originate. This is especially true of the outpour from the Mediterranean later to be discussed. Near the great intercontinental dam over which the waters pour in both directions, much mixing and irregularity of motion and constitution is to be expected, and present data are quite inadequate for a discussion of details. Here, however, the general fact of a difference in thickness of the polar and the Atlantic water-columns will perhaps suffice. At any rate, this difference between the polar and Atlantic columns is only a striking intensification of what should arise normally in less degree in all similar cases, for the polar water-column should be relatively thickest in its cold, dense, basal layer and the Atlantic in its warm, saline layer, and these dominant layers should actuate the circulation so far as dependent simply on temperature and salinity. A comparison of the two columns is thus a necessary step toward interpreting the great features of the polar-Atlantic interchange so far as dependent on density, and density is the radical feature of oceanic circulation. Let us then consider these two columns, bearing in mind, however, that the layers of water are not stationary, but moving; that they are not fixed in temperature and salinity, but always changing toward equilibrium.[1]

THE THREE MAIN LAYERS OF THE COLUMN OF THE POLAR SEA

From the determinations of Nansen[2] and others it appears that a typical column of the waters of the Polar Basin from surface to bottom embraces three main layers:[3]

[1] The data from which these generalized comparisons are made have been gathered chiefly from Murray's well-known publications, particularly the *Challenger Reports*, *The Ocean Depths*, and *The Ocean;* the papers of Nansen and associates, particularly *The Scientific Results of the Norwegian North Polar Expedition* (1893–96); Jenkins' *Textbook of Oceanography* (1921); and James Johnstone's "Oceanography," *Enc. Brit.*, new Vol. XXXI (1922).

[2] "Norwegian North Polar Expedition," *Scientific Results*, Vol. III.

[3] Nansen gives four layers, but for the present general discussion the distinction between the two upper, rather thin layers seems immaterial as both are cold layers of less than mean salinity, and have a common origin in surface conditions. These two layers are thus defined by Nansen:

"(1) A surface-current of water with low salinity (from about 29 o/oo to about 32 o/oo, perhaps 20 or 30 m. deep, running towards the northwest and west;

"(2) An underlying, slow current of water with a higher salinity and a very low temperature, running in a different direction, and consisting of surface water from other parts of the Polar Sea. The absolute minimum of temperature is situated in this current, at about 50 or 60 m."—*Ibid.*, Vol. III, p. 346.

1) *An upper layer* of very cold water whose salinity is relatively low (ranging from 29 to 32 parts per thousand in the more surficial portion, and somewhat higher in the bottom portion) and whose density, because of this low salinity, is less than that of the warmer but more saline layer next below. This upper layer is the source of the ice-laden outlet streams of the Polar Sea previously mentioned. The freshening water which reduces the salinity of this layer comes from precipitation on the sea surface, from the drainage of adjacent lands, and from the melting of ice.

2) A middle layer of warmer but more saline and denser water. Its salinity ranges from about 35.1 to 35.3 parts per thousand (Nansen).

3) *A bottom mass*, very much thicker than both the foregoing layers taken together, and denser than either, because it is both cold and saline. It is the abysmal water of the Polar Basin. So far as known, it occupies all the basin but the upper 800 to 1,000 meters. Nansen gives its mean salinity as 35.29 parts per thousand; in other words, it is slightly more saline than the middle layer. Its mean temperature is about 1.56° C., which is not so low as the basal portion of the upper layer. It holds notable quantities of the atmospheric gases, which implies that even these basal waters take part in a cyclic motion that has its contacts with the air at some stage. They are not stagnant waters, although their motion is probably very slow.

THE SOURCES AND RELATIONS OF THE LAYERS

The two variables by which the waters of the ocean are distinguished are temperature and salinity. The variations of temperature are functions of insolation and radiation and, in a general way, vary with latitude. The variations of salinity depend on the excess or deficiency of precipitation over evaporation, which, is in turn dependent on the ascent or descent of the regional atmosphere. The mean salinity of the ocean is usually taken as about 35 parts per thousand. The salinity varies also with latitude, but in a different way and with greater departures from the general rule. In the very high and the very low latitudes, precipitation generally exceeds evaporation, and the sea-waters suffer dilution. In a belt between these, conveniently known as the 30° belt, evaporation is generally

greater than precipitation, and the sea waters suffer increase of salinity. The distribution of these areas of dilution and increase of salinity are subject to much modification that must be specially considered in any given case. The real cause in the main is the ascent or descent of the atmosphere.

1. *The source of the upper layer.*—There is practically no ground for doubt that the upper layer of water of the Polar Basin is derived from the upper layer of the Atlantic waters with the addition of the excess of precipitation of the region, the inflow from adjacent lands, and the melting of the ice. As the mean dilution of standard sea-water caused by these fresh waters is of the order of 15 per cent, it is clear that the main source of salinity is in the Atlantic waters, whose salinity reaches and in some parts passes the mean salinity of the ocean.

2. *The source of the middle layer.*—There is no doubt that this layer also comes over the intercontinental ridges from the Atlantic, for that is the only assignable source for its combined salinity and warmth, but there is a rather vital question as to the particular part of the Atlantic column from which it comes. This layer is described by most writers as though it had occupied a surface position in the Atlantic, as also when it passed over the Southern Intercontinental Ridge, but that it became cooled and sank to its present middle position later. If by this it is intended to affirm that these middle waters of the Polar Basin are those that formed the "Gulf Stream," or strictly surficial waters of the Atlantic, there appear to be two objections to it: (*a*) the salinity of the middle layer in the Polar Basin (35.1 to 35.3 per mille—Nansen) seems too high to have suffered surface dilution while it was drifting 3,000 miles into a zone in which precipitation is greater than evaporation; and (*b*) if the Gulf Stream—or the surface layer under any other name—sinks to form this middle layer of the Polar Basin, what source remains for the upper layer in the Polar Basin? It seems more consistent with all the considerations that weigh in the case to regard this middle polar layer as a northward extension of the similar *middle* layer of the Atlantic which will be described later. In a loose sense, this middle polar layer may be regarded as a part of the "Atlantic

Drift," if that term is understood to include all the warm waters that flow north over the intercontinental ridge, whether in strictly surficial or deeper levels, but the middle layer of the Polar Basin can scarcely be assigned to the Gulf Stream if that term is confined, as it apparently should be, to such surface waters as were scarcely normal in salinity when they left the Gulf of Mexico and afterward traveled 3,000 miles in zones where precipitation is generally greater than evaporation. These considerations will take on more force when compared with the middle Atlantic layer discussed later.

3. *The source of the bottom layer of the Polar Sea.*—The thick abysmal mass of cold saline water which forms the bottom layer in the Polar Basin is assigned by Nansen to the cooling of the middle layer by contact with colder water. That the bottom layer is derived in some way from the waters above seems quite beyond question, for the Southern Intercontinental Ridge cuts off the cold abysmal waters of the Atlantic and there seems no other source for the low temperature than the surface effects of the Polar climate. But the view that the middle warm layer was cooled to the requisite degree by any form of simple contact with the upper waters seems incompatible with the observed salinities. The mean salinity of the abysmal mass is given by Nansen as 35.29 parts per thousand. The mean salinity of the warm middle layer is slightly less than this, and the salinity of the cold waters of the upper layer is notably less than this. Any simple commingling of the two upper layers should give too low salinity to the lowest layer. Nansen holds with good reason that the bottom waters should be heated rather than cooled from below, and gives observational evidence in support of this. He also holds that the lower part of the upper layer, which is colder and more saline than the uppermost portion, arises from freezing at the surface. Freezing, as is well known, forces out of the forming ice the larger part of the salts and gases previously held in the congealing water. This salt added to that in the layer of water next below gives it higher salinity. Sometimes it rises to the quality of a brine. At the same time it gives coldness, which is sometimes intense. Nansen, however, is inclined to limit these effects of freezing to his second layer—that is, to the lower part of what is here called the upper layer. He thinks that a small and slowly formed

film of brine would be unable to sink through the warm layer next below and give rise to the cold abysmal layer at the bottom.

So far as concerns such freezing as may take place on the under side of the *thick* Arctic ice already formed, this view seems well taken, for the freezing beneath the thick ice, even in the Arctic regions, is slow and limited in amount. The layer of briny water formed by it is thin and subject to mixture while in the process of forming, for more or less of motion between the ice mantle and the water below arises from tides and winds.

But there is a *special* type of freezing action that is much more rapid, while at the same time the film of brine it forms is subject to prompt downward, edgewise propulsion. This requires a careful study of details.

A combination of rapid freezing, brine formation, and downward propulsion.—While freezing under the cover of thick ice that generally mantles the Polar Sea is slow, very rapid freezing takes place in the cold season where open lanes of water are formed rather suddenly by the action of winds and tides. According to Peary and other explorers who have traversed the Polar Sea in the freezing months, the opening of such lanes is frequent and often sudden. Just where and when they will open cannot be foretold, and they are often so swift in action that it is wise to sleep prepared for a possible plunge into the icy waters of the opening chasm. The lanes are often so wide and long as to constitute a most serious obstacle to reaching the pole over the ice-fields of the Polar Basin. Peary describes these lanes or "leads" as being "sometimes mere cracks," "sometimes just wide enough to be impossible to cross," and "sometimes rivers of open water from half a mile to two miles in width, stretching east and west farther than the eye can see."[1] He says that the old floes which are traversed by these "leads" are not simply the products of freezing in place but are formed by the crumpling, crushing, and piling up of such original ice by the almost irresistible power of the great polar ice-sheet, or

[1] Robert E. Peary, *The North Pole* (1910), p. 197. Peary's narrative of his trip to and from the pole (pp. 236–85), gives a very realistic impression of the frequency and extent of the formation of these "leads," and especially of the formidable nature of the "Big Lead," formed over the edge of the continental shelf, in which Marvin lost his life.

some large part of it, when put in motion by winds or tides or both combined. He gives the thickness of the old floes traversed by the "leads" as ranging from less than 20 to more than 100 feet. On the important point of the relative proportion of the ice-field exposed by the lanes to rapid freezing, he writes:

> At least nine-tenths of the surface of the Polar Sea between Cape Columbus and the Pole is made up of these floes. The other one-tenth, the ice between the floes, is formed by the direct freezing of the water each autumn and winter. This ice never exceeds eight or ten feet in thickness.[1]

It thus appears that in the course of the cold season of each year about 10 per cent of the surface of the Polar Basin may freeze in the way subsequently described, or in the course of ten years the whole surface or its equivalent may so freeze.

Peary's narrative shows that even in March and April these leads form suddenly, and that the temperature of the air at the time is often 40° below zero; it shows further that high winds are then frequent and strong. The offsets of the trails recently made by the explorers indicated that differential movements of the ice-mantle were taking place and were considerable in amount.

Putting the significant items together, it appears that the water-lanes formed in the old ice-floes must be bordered by ice-walls on either side whose vertical faces range as high as 100 feet. The larger part of these vertical faces are below the surface of the water and form bounding walls to the water that arises into the chasm as it opens. Thus the water that fills the lane stands above the common mass below as a raised block or prism. It is the surface of this raised prism of water that is exposed suddenly to very low temperature and often to wind action at the same time. The surface must therefore freeze very promptly, whether it is still or is agitated. More or less agitation is apparently the more common case. If agitated by wind, the surface water should form a sludge of mixed forming ice and residual water. This residual water should be charged with the salts forced out of the frozen portion of the water. This is added to the previous content of salt, giving rise to a brine. The sludge thus formed when the wind is blowing will be driven *edgewise* over the surface until it encounters the vertical ice-face

[1] *Op. cit.*, pp. 195–96.

that borders the lane. Here the ice of the sludge is likely to be packed and piled up at the surface while the briny water within it has no alternative but to turn downward along the face of the wall of ice at the edge of the lane. The sludge thus driven forward and separated into packed ice and brine exposes new water behind which undergoes the same process, so that the movement edgewise is constant until the surface is sheeted over with ice thick enough to suppress the waves raised by the wind and bring on a new form of action, to be discussed below. When the edge of the sheet of brine is turned downward in front of the bordering ice-wall, the push from behind continues as long as the wind pushes the water or its motion continues by momentum. This push is edgewise, that is, in the line of least resistance. It is also in the line in which it is itself impelled to go by its density, which is greater than that of the adjacent water. Here then is a combination of push and pull in the line of least resistance, which is felt so long as the force of the wind is felt by the freezing surface.

It seems reasonable to assume that the briny sheet, once it is turned downward at its edge and projected in that direction, will continue downward, for that is the direction demanded by its density as well as its temporary momentum. Now it is not necessary that this action should continue long, for if the brine sheet moves forward and downward no more than 800 to 1,000 meters—which is often less than the width of the lane—its forward edge will have crossed both the upper and middle layers and have entered the basal layer.

This briny layer, while not great in volume, will be exceptionally cold as well as saline, and will carry both low temperature and high salinity into the basal layer, thereby adding little by little the qualities it requires to correspond to its observed characteristics. These little increments will be added here and there, for the lanes open at haphazard, and the briny sheets are driven into the basal layer at haphazard intervals of both space and time. They will thus be favorably distributed for mixture and diffusion. The abysmal mass is itself in motion, for, as Nansen has shown, it is a current, though probably a very slow one. The action, however, continues year after year for a long period, so that the combination is favorable to an ultimate homogeneous mass.

Perhaps, at first thought, this process will seem to involve the destruction of the warm middle layer, and its existence may seem to be a reason to doubt the verity of the process. The middle layer is of course constantly disappearing by the process but is disappearing only little by little very locally where crossed by the briny film. The middle layer is, however, a *current*, and is being continually renewed. It may thus be preserved, though continually suffering loss. The detail of the operation is important to a clear view. The thin, cold, briny sheet in passing down across the middle layer of course exchanges temperatures and salinities with it at the immediate contact surfaces, but very little elsewhere. This exchange gives the contact portion of the middle layer greater density than the main portion of that layer, and hence this contact film tends to go down with the briny layer and become part of the basal layer rather than remain as a cooled portion of the middle layer. The rest of the middle layer thus retains its temperature almost unmodified. The gradual loss thus sustained by the middle layer is supplied by onflow as a mass from the original source, that is, as interpreted below, from the Atlantic middle layer.

The more special phase of the action has been here described. There is a more general phase. After the surface of the water in a lane freezes over, the vertical walls that border the lane remain, as a rule, until the new ice is crushed by the closing of the lane. So long as the prism of water in the lane thus lasts, any movement of the ice over the water, or of the water under the ice, almost necessarily forces any briny film that may have formed on the top of the prism by continued freezing to move edgewise and thus to encounter the border wall and be turned downward, much as in the previous case. Now, the winds and tides are almost always causing differential movements between the ice-cover and the water on which it floats, and so this downward, edgewise, penetrating action may not be so special as it seems.

Atmospheric confirmation.—An interesting atmospheric abnormality has been observed in Grinnell Land by Moss and in Greenland by Krogh, which falls in with this view of salt concentration by freezing and seems to rather pointedly confirm it. These observers, quite independently and at different dates, noticed that when the wind at the localities of observations came from the northwest,

the direction in which the assigned freezing action is supposed to be most effective, the amount of carbon dioxide in the air often rose very notably, sometimes reaching double the normal amount or even more.[1] The most plausible explanation of such an enrichment in carbon dioxide in lands of low temperature where rapid decay is out of the question and where volcanoes are unknown, is the inference—in itself almost a necessary one—that the cold water of the Polar Sea is, as a rule, highly charged with carbon dioxide at all times because of its coldness, and that the freezing of such charged water in the lanes forces out the larger part of this high content of carbon dioxide into the briny layer formed by such freezing, and that a portion of this excess charge escapes into the air, as required by the law of gaseous equilibrium.

THE THREE MAIN LAYERS OF THE ATLANTIC COLUMN

For the purposes of a comparison with the waters of the Polar Sea, the waters of the Atlantic, though more markedly differentiated, may also be grouped into three layers analogous to those of the Polar Basin, an upper, a middle, and a bottom layer. This parallelism is not only convenient for our study, but the three divisions represent the great factors in the oceanic circulation of this region so far as these depend on density, which is the chief cause of oceanic stratification other than surficial wind action.

1. *The upper layer* has considerable diversity. Its chief factors are (*a*) poleward-moving, warm surface currents, and (*b*) equatorward-moving, cold surface currents. These, however, do not cover the whole surface. There are besides, (*c*) surface sheets, the salinity of which is being increased by evaporation, and this increase tends to cause them to sink into the middle layer, so that they are surface layers only in a transient sense. There are also, (*d*) waters that well up from below and bear the nature of lower layers until they have been "weathered" into surface layers. The last two are instructive in that they represent the system of interchange between the upper and lower layers and the process of transition from the one to the other. The first two are the normal surface sheets.

[1] Moss, "Notes on Arctic Air," *Proc. Royal Dublin Soc.*, Vol. II; Krogh, "Abnormal CO_2 Percentage in the Air of Greenland," *Meddelser on Greenland*, Vol. XXVI (1904), pp. 409–11.

a) *The Greater Gulf Stream.*—The best-known portion of the warm, poleward-moving surface currents has long been called, with some looseness, the "Gulf Stream." For the general purposes of this discussion, it will be convenient to acknowledge this looseness frankly by using the broad term, the "Greater Gulf Stream," which implies there is a narrower sense. Under this broad term let us include all warm surface currents which directly or indirectly unite in carrying heat into the polar regions. This great group may be said to start with the warm, equatorial currents that flow northwesterly along the northern coast of South America, gathering as they go the fresh waters of the Amazon, the Orinoco, and other rivers of South America, as well as the direct precipitation of the rainy region they traverse. They are both warm and diluted. For the larger part they enter the Caribbean Sea and through it reach the Gulf of Mexico. In passing through these bodies they receive further dilution from the rivers of the bordering coasts, notably the great rivers of the Mississippi Basin. As is well known, the configuration of the coasts turns these equatorial waters about to the northeast and they issue from the gulf as the Florida current or the true Gulf Stream.

A part of the equatorial current, however, turns to the northeast outside the Antilles and flows more or less parallel to the true Gulf Stream until the two become practically indistinguishable from each other.

While the Gulf Stream is moving northeasterly near the coast of North America, it appears from the maps of salinity (see Fig. 2)[1] to become rather suddenly much more saline than it was in the Gulf of Mexico, and this holds measurably true far to the northeast. The map of salinity probably requires much revision in detail to represent the specific facts, for the data for a map of salinity are as yet very imperfect. Murray's chart is here accepted in its essentials, with the presumption that fuller data will modify it in important particulars. On Figure 2 it will be seen that there is notable westward extension of the area of high salinity that centers in the heart of the great evaporating tract, or, in other words, the Sar-

[1] Sir John Murray, *The Ocean*, Plate III (in colors). This is reproduced in colors as a frontispiece in J. T. Jenkins' very recent (1921) *A Textbook of Oceanography*. Figure 2 of this article is a photographic copy of this.

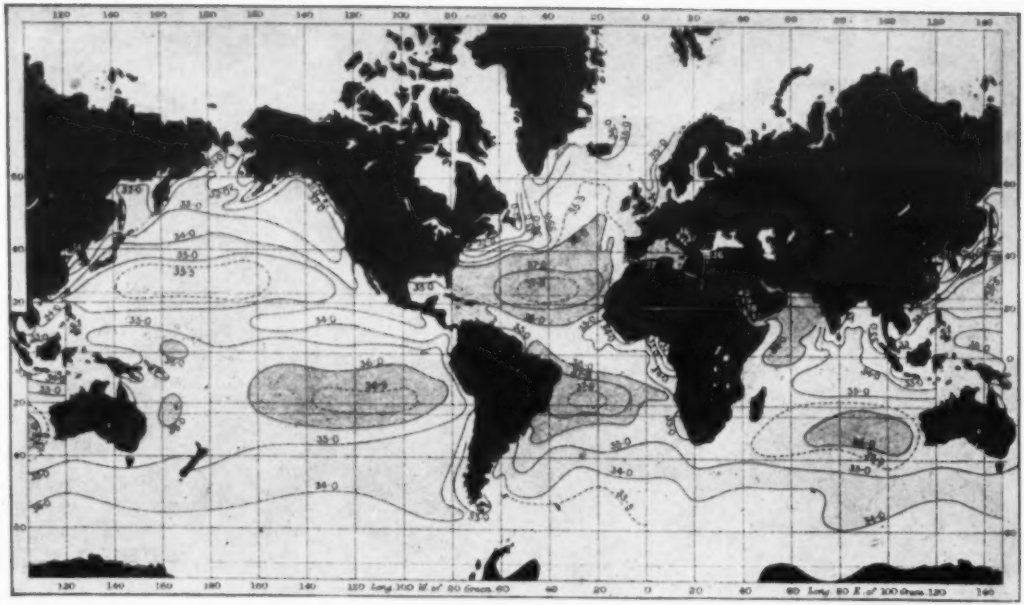

FIG. 2.—Photographic copy of Murray's "Map of the Surface Salinity of the Ocean," *The Ocean*, Plate III. Actually taken from frontispiece to Jenkins' *Textbook of Oceanography* (1921).

gasso area. A slight amount of the increase in the salinity of the Gulf Stream east of North America may be assigned to excess of evaporation over precipitation in crossing "the 30° dry belt," but the amount of this seems insufficient to explain the salinity represented on Murray's map. The data seem to imply that there is a reciprocal action between the saline waters of the main evaporating or Sargasso Basin and the adjacent edge of that part of the Gulf Stream which circles about it, by which the two classes of water are intermingled or interdigitated. The waters of the Gulf Stream proper are the fresher and lighter; the waters of the Sargasso region are constantly growing more saline by reason of excess of evaporation over precipitation. Under these conditions an interaction of the two types of waters is likely to take place, assuming the form of spiraloid currents subordinate to the main movement of the encircling Gulf Stream. There would naturally attend this an intermixture or interweaving of waters of a complicated digitate, gyratory sort. This view gains not a little support in the anomalous drifts of wreckage. While the Gulf Stream has a very definite northeasterly movement in this region, the drifts of wreckage are often very strangely at variance with it in details. These peculiarities imply that the Gulf Stream, when studied in detail, is far from being a simple, straightaway current. It seems to be affected by whirls and various anomalous movements of a minor sort. The singular northeastward extensions of the 26°-per-mille salinity line (see salinity chart, Fig. 2), at about 20° West Long. in mid-ocean, fall in with this view. This feature seems rather clearly to imply that the edge of the saline waters of the evaporating area are involved in the northeastward movements of the adjacent Greater Gulf Stream. At any rate, this view seems best to fit the distribution of supersaline waters compared with subsaline waters of the mid-Atlantic, so far as now known. We shall return to this subject in considering the middle stratum of the Atlantic column.

When a little past the middle of the Atlantic, the Gulf Stream sends off a southward, recurving branch, which flows around the east end of the Sargasso area and connects with the North Equatorial current and thus at length completes the loop about the Sargasso Basin. It is important here to note also that, on its outer

side, this loop of the Greater Gulf Stream gives off a branch into the Mediterranean Basin, and that out of this branch of the Gulf Stream group there arises later by evaporation the lower Mediterranean stratum, which in turn forms part of the *middle* layer of the Atlantic waters. This I shall emphasize later. The point is that here is a declared case of the passage of the upper layer consisting of one type of waters into a middle layer of another type of waters, and this middle layer later plays an essential part in the explanation of polar ameliorations here offered, and in later applications of a more general nature.

The main branch of the Greater Gulf Stream flows onward to the northeast, and greatly affects the climate of northwestern Europe, as is well known. A large portion of the Gulf Stream passes over the Southern Intercontinental Ridge, and in the tract between the two intercontinental ridges is much modified by branchings, interdigitations, whirls, and various irregularities. Passing on over the Northern Intercontinental Ridge, this much modified stream, as here interpreted, forms the main source of the upper layer of the Polar Sea described above. We will return to this last point in connection with the middle Atlantic layer.

All this group of currents, here called for convenience the Greater Gulf Stream, are surficial, warm, and rather low in salinity, except as their salinity is increased by interchanges and interdigitations with waters of the adjoining saline layers.

b) *The cold currents of the polar outflow.*—Over against these warm, surficial waters flowing poleward, stand a group of cold polar currents flowing southward. Their primary source is in the icefield of the surface layer of the Polar Basin. These are gathered into the Labrador current as their main trunk stream at the south. These occupy the surficial position of the Atlantic column on its west side, corresponding in that respect to the Greater Gulf Stream on the east side. The two may be regarded as the complements of each other. The climatic function of the one is to carry heat northward; that of the other is to carry cold southward. But this is done at great loss, for both are surficial. Moreover, their waters, instead of being altogether the same throughout their journeys, are constantly changing by intermixture with other waters as a part of

the tendency ever present to move toward an equilibrium of salinity and of temperature.

When the Labrador current encounters the Gulf Stream at the eastern angle of the American continent, formed by Newfoundland, great irregularities and interdigitations of current are developed and its further course becomes obscure.

c) *The surface concentration of salt.*—The foregoing warm northward-going and cold southward-going currents receive practically all the fresh waters shed from the adjacent lands. They also receive nearly all of the fresh waters that fall in areas where excess of precipitation over evaporation prevails, and practically all the melt waters of the Arctic ice-floes and icebergs. Taken together, they embrace nearly all of the surface waters that are much subject to dilution. This dilution is the chief reason why they remain surface waters.

Over against these areas of surface dilution stand the areas in which evaporation exceeds precipitation and the surface waters grow more and more saline. This increasing salinity adds to their density and gives them a tendency to descend, so that, while it is necessary to recognize that, for the time being, they are surface waters, and so in a formal sense part of the upper strata of the Atlantic column, they are really the initial stage of a lower layer composed of more highly saline and hence denser waters even though they remain warm. The evaporating areas center on "the 30° dry belt," but this belt is crossed by storm tracts near the western border of the Atlantic, chiefly in the gulf region. Nearer the center of the ocean a large area is developed in which descending air prevails rather persistently, and evaporation is notably in excess of precipitation, the Sargasso area. In addition to the Sargasso area in the mid-Atlantic, the Mediterranean region is a marked area of concentration of salt by evaporation. It is the more distinctive because it is isolated from the ocean except for its slender connection through the Straits of Gibraltar. It is a peculiarly instructive type. The saline waters of these two tracts will be further considered in connection with the middle Atlantic layer to which they give rise.

d) *The upwelling areas.*—It is only necessary merely to mention these tracts here for the sake of completeness. They are smaller

than the foregoing, and are mainly secondary to movements in other parts of the ocean body. In their natures these waters belong to the deeper layers from which they come.

The middle Atlantic layer.—The origin of the middle layer of the Atlantic column is most clearly illustrated by the transformation that takes place in the isolated basin of the Mediterranean. As previously noted, a side current from the southward-flowing branch of the Gulf Stream west of Spain enters the Straits of Gibralter and forms the upper layer of the Mediterranean in its western portion. As it creeps eastward, its salt content is concentrated by evaporation in spite of the fresh waters that flow into it from the adjacent lands. By the time it has reached the east end of the Mediterranean, it has attained a salinity of 39 parts per thousand. In spite of its warmth this salinity gives it a density sufficient to make it sink and creep back westward as the bottom layer. This at length flows out into the Atlantic as a bottom current in the lower part of the Straits of Gibraltar. On entering the Atlantic, it sinks by reason of its saline density through the upper oceanic waters, and spreads out in delta fashion, until it reaches a depth of about 2,000 meters, where its base finds a horizon of equilibrium. On its left hand, it has been traced about 10° southwestward. On its right hand, it pushes northwestward and has been detected as far as 52° to 53° N. Lat., or half way to the mouth of the Baffin Bay inlet. Beyond this point, data are so scant as to leave its further extension obscure. It seems probable that it merges on the west with the similar waters rendered saline by evaporation in the Sargasso area and that the two together make up a true middle layer distinct from that below by reason of its warmth, and fairly distinct from that above by its higher salinity, though, of course, it is constantly grading into the contact waters above and below, by various forms of commingling and diffusion.

A portion of the middle layer, in this large and general sense, appears to creep southward to compensate, in part, for the surficial equatorial waters shunted into the North Atlantic by Cape St. Roque, while another part creeps northward to maintain, by interchange according to the laws of equilibrium, the salinity of the northern waters. Waters of adequate salinity must obviously flow into

the northern regions to account for the fairly close approximation of the middle and bottom layers of even the Polar Basin to the mean salinity of the whole ocean. The concentration of salts by excess of evaporation over precipitation is the sole dependence of any moment for offsetting the dilution of the tracts where precipitation is greater than evaporation. The high latitudes belong to this latter class of areas, and adequate saline waters must flow into these regions to maintain the observed salinity of their waters.

As the weir formed by the Southern Intercontinental Ridge, though not yet fully explored, has a water depth of about 600 meters at least, there is room for a warm, saline middle current as well as the somewhat diluted and cooled surficial current—the Gulf Stream factor—to flow over it poleward. Both classes of water are recognizable in the Norwegian Sea beyond. The only point of present divergence from current opinion—if indeed there is really any at all—lies in the assignment of the partially diluted and somewhat cooled waters flowing over the weir northward to the Gulf Stream group, and in the assignment of the more saline and warmer class of waters going over the weir *to the middle layer* which better preserves its warmth and salinity because it flows *under cover*.

The bottom Atlantic layer.—Where the Mediterranean layer of warm saline water pours out in delta form into the Atlantic, it forms a well-defined middle layer. This gives place below at about 2,000 meters' depth to a still heavier layer which is both saline and cold. This fills the abyssal depths of the whole Atlantic Basin, and similar waters occupy the depths of all the oceans. These abyssal waters of the Atlantic are of the same type as the bottom waters of the Polar Basin. They are thought to be derived from them in part at least, for this seems to be the only adequate line of outflow, for the abyssal waters of the Polar Basin and, as noted before, their nature seems to show that they are a part of a persistent and effective circulation. The abyssal waters of the North Atlantic seem, as present data stand, to be more saline and heavier than those of the more southerly oceanic basins. They should hence tend to flow outward toward these in part also; this would tend, in turn, to offset the surficial waters shunted into the North Atlantic by Cape St. Roque. This interchange would help toward the equaliza-

tion of the salinity of the whole ocean which, in the long run, must be preserved. All our postulates seem thus to tend to general equilibrium and at the same time recognize the excess of evaporation over precipitation in the North Atlantic drainage area taken as a whole.

THE APPLICATION OF THE FOREGOING TO THE SPECIAL CASE IN HAND

The purpose of the foregoing rather wide-ranging discussion is to bring out the general features of circulation from which the ameliorating current of Baffin Bay is derived by a natural rather than a strained hypothesis. In itself, the Baffin Bay branch is a small affair, but its peculiarities make it refractory to the usual line of interpretation. It is hence suggestive and significant. As a feature of the "Gulf Stream" or of the northeasterly "drift of the Atlantic" surface waters as ordinarily understood, the localization of the warm Baffin Bay current diverges from ordinary oceanic modes of movement. Its line of projection is northwestward from the center of generation of the warmth and salinity it carries poleward, while the normal direction due to the influence of the earth's rotation is northeastward. Yet the rotational influence is as obvious on this current as on others, after it has entered Baffin Bay. The rotational effect is of course always active, but in the massive movement of the deeper part of the middle layer of the Atlantic Basin it is overcome by co-operating influences now to be noted. As a slow undercurrent in the embrace of currents of different trend above and below, and as a mere offshoot from the great middle layer of the Atlantic column, its explanation takes on a special phase dependent on these conditions. In the region where it is generated, the middle Atlantic layer is 2,000 meters thick, *less* the depth of the Greater Gulf Stream that floats above it. The true Gulf Stream, as it is crowded through the Florida Straits, is credited with a depth less than a third of this, and as it spreads out in the higher latitudes its depth is undoubtedly still less. The middle layer, as here interpreted, thus extends much below the crest of the weir formed by the Southern Intercontinental Ridge. This ridge stands *obliquely athwart* the natural line of northeastward flow of the warm middle

and upper Atlantic layers in their normal circulatory courses. Only the upper layer (the Greater Gulf Stream) and the upper part of the middle Atlantic layer are permitted to flow directly on over the obliquely set weir. The lower part of the thick middle layer is shunted to the northwest by the oblique attitude of the weir.

A natural effect of this oblique divergence by an intercontinental dam whose side is much buttressed by submerged ridges is more or less of tortuous and rotational subcurrents, some of which should appear at the surface in more or less modified forms. This effect should be cumulative toward the west side of the weir or the northwest corner of the Atlantic, in other words, the angle between the oblique weir and the east coast of North America. Indications of this shunting and the incidental deformation of currents and distributions is shown on the accompanying salinity map (Fig. 2), especially to the south and the southwest and west sides of Iceland and off the mouth of the Baffin Bay inlet. The climatic conditions of Iceland are in themselves very suggestive, for Iceland is far toward the western end of the weir and on the west side of the Atlantic. It is, moreover, at that end of the weir over which the cold polar waters pour in going southward. On the same salinity chart, but farther from the axis of the ridge-dam and obviously controlled by the south-projecting point of Greenland, is a notable loop of the salinity curves toward the mouth of Baffin Bay. These, to be sure, are surface features, but they probably represent and depend upon a deeper movement. They definitely suggest the divergence of an undercurrent such as that which gives rise to the striking ameliorations of climate in Baffin Bay. Such an undercurrent shunted into the Baffin Bay trough offers a very natural explanation of the singular way in which the East Greenland polar current of lighter ice-laden water curves so sharply about the southern point of Greenland and is carried northward in crossing the mouth of the Baffin Bay trough, because the latter floats on the former and is carried in due degree along its course.

With such intimate relations to much colder and less saline waters, the Atlantic offshoot into Baffin Bay becomes reduced in temperature and in salinity in its 1,500 mile advance to the head of the bay, but still it gives striking evidence of being more effective

climatically when it is forced to the surface at the head of the bay than is the more direct surficial Gulf Stream when it reaches the same latitude in Spitzbergen.

The lessons of the study seem to be (1) the superior climatic efficiency of undercurrents compared with surface currents, (2) the superior potency of the middle layer of the Atlantic. (3) The effects of confinement compared with spreading are also pointedly illustrated but in reality the results are more a matter of form than of real quantitative effect when the sum total of climatic influence is considered.

THE PHYSICAL CHEMISTRY OF THE CRYSTALLIZATION AND MAGMATIC DIFFERENTIATION OF IGNEOUS ROCKS

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VIII

THE TEMPERATURE-INTERVAL OF THE CRYSTALLIZATION OF THE IGNEOUS ROCKS

We will take as the starting point for the calculations in this chapter the determinations made at 1 atmosphere pressure (in water-free melts) of the minerals, the eutectics, the mix-crystals, the liquidus- and solidus-curves, etc.

We will then have to make two corrections: (*a*) on account of the effect of pressure, and (*b*) on account of the effect of light volatile compounds dissolved in the magma (H_2O, CO_2, etc.).

As explained in an earlier chapter[1] the melting points of the silicate minerals increases with the pressure, but only in a *relatively* insignificant degree. In flows, for instance, we have to deal with only 2.5° or at most 10° C., and even in deep-seated rocks crystallized at very great depths, the rise of the temperature may be only about 25 or 50° C. Hence the effect of pressure is practically out of the question. But not so with the effect of H_2O, CO_2, etc., to which we will return below.

As typical examples of *anchi-monomineralic rocks*[2] we will choose the *anorthosites and the peridotites*. The solidification of $Ab_m\ An_n$ (without any admixture of foreign materials), according to Bowen's investigations, in water-free melts at 1 atmosphere pressure, takes place at the following temperature-intervals, when we assume

[1] This *Journal for* 1922, p. 611–614.

[2] In a later paper I shall try to prove that these rocks must have crystallized from ordinary, thoroughly melted magmas. I cannot agree with Bowen's exposition of the anorthosites as formed in a kind of magma-gray with large quantities of plagioclase-crystals and in addition a magma in subordinate quantity.

complete equilibrium between the solid and the liquid phase as in the case of most deep-seated rocks:

	Start	End
$Ab_1 An_5$	1521°	1465°
$Ab_1 An_2$	1490°	1372°
$Ab_1 An_1$	1450°	1287°

With incomplete equilibrium the crystallization of the final melt would have taken place at a somewhat lower temperature.

In *anorthosites*, with only 4–10 per cent of pyroxene, olivine, iron ore etc., the last mentioned minerals, according to *Bowen's* diagram for the system Ab : An : diopside, will occasion only a relatively small reduction of the temperature for the beginning of the crystallization of the plagioclase. The relatively small quantity of end-magma in these rocks, will at a late stage of the solidification crystallize along a eutectic boundary-line (or plane) at a much lower temperature, about 1225–1200°.

For the various anorthosites poor in foreign minerals (calculated at 1 atmosphere pressure and assuming water-free melts) we will have the beginning of crystallization in the bytownite rocks at about 1475–1500°; in the relatively An-rich labradorite-rocks, with $Ab_2 An_3 - Ab_1 An_2$, at about 1450°; and in labradorite-rocks, with about $Ab_1 An_1$ at about 1400°. Following this, the main part of the plagioclase will crystallize at a little lower temperature, down to or a little below 1300°. Finally, comes the crystallization of a small quantity of end-magma at a somewhat lower temperature, about 1200°.

For *dunite*, consisting chiefly of an iron-poor olivine (most frequently about 0.09 Fe_2SiO_4 . 0.91 Mg_2SiO_4, sometimes even with as little iron silicate as 0.075 Fe_2SiO_4 . 0.925 Mg_2SiO_4) with a small percentage of picotite, chromite, bronzite, etc., the crystallization[1] must have started at as high a temperature as 1500°. With very little admixture of foreign minerals and at the same time with an olivine especially poor in iron, the temperature may have been a little higher, as 1550–1600°. The main part of the crystallization will take place at a temperature higher than 1400°, and

[1] Cf. this *Journal* for 1921, Fig. 22, p. 522.

only a small quantity, existing as a eutectic end-magma, at some lower temperature.

A great part of the crystallization of other peridotites with much olivine (most frequently between 0.10 Fe_2SiO_4 · 0.90 Mg_2SiO_4 and 0.15 Fe_2SiO_4. 0.85 Mg_2SiO_4) and a little more bronzite, diopside or diallage, etc. (mostly 15–40 per cent) than in the first case will have taken place at a high temperature, about 1400°. The same is also true for bronzite rocks.

We will now discuss the most important *anchi-eutectic* rocks.

As a starting point for *the gabbros* and *the norites*, we have the eutectic boundary-line determined by *Bowen* between Ab+An and diopside, with temperatures (as before at 1 atmosphere pressure and in water-free melts) from about 1260° for 51 diops. : 49 Ab_1An_4 to about 1215° for 28 diops. : 72 Ab_7An_3. If we substitute ordinary iron-bearing hypersthene or diallage for the iron-free diopside this will result in the lowering of the above-mentioned temperature but not to any specially important degree. Most gabbros and norites contain a small surplus above the eutectic boundary, in some cases of plagioclase and in others of a ferromagnesian silicate. Hence the crystallization will most frequently commence at 1250° or 1275°, and the main part crystallize along a eutectic boundary at about 1225–1200°. For some gabbros and norites, diabases, basalts, etc., however, we will have to assume a still lower end temperature. These values, calculated from the physico-chemical diagrams (for water-free magma at 1 atmosphere pressure) are confirmed by an experiment made by Sosman and Merwin[1] concerning the melting of a diabase from Granton, New York: "The remelting begins at about 1150° and is practically completed somewhat below 1300°. The rock flows readily at a temperature about 1225° at which temperature all is fused excepting about a third of the feldspar. A little feldspar still remains undissolved at 1250°, but only traces remain at 1300°."

The *diorites*, owing to the somewhat higher per cent Ab in the plagioclase, must have a little lower crystallization-interval than

[1] *Jour. Wash. Acad. Sci.*, III (1913). See also Day, Sosman, and Hostetter (*op. cit.*), *Amer. Journal. Sci.*, XXXVII (1914).

the gabbros and norites. The difference, however, cannot be very important.

The syenitic rocks.—According to precision investigations at the Geophysical Laboratory in Washington, the melting-point of pure Ab ($Na\,AlSi_3O_8$) or, to be quite exact, of 98 Ab+2 An, is 1100°±10°. Dr. Arthur L. Day of Washington, recently wrote me that, for pure Or ($KAlSi_3O_8$) we will have to count on about 1200°, "a full hundred degrees higher than that of albite,"[1] but that precision-determinations are extremely difficult owing to the high viscosity.

The Norwegian mineralogist, Th. Vogt, in a speech in Christiania Videnskapsselskap, April 16, 1920—after the first section of this work had already been sent to Chicago for publication—analytically defined the binary system Or : Ab more closely,[2] and further established the fact that we here have to deal with a mix-crystal eutectic system. The eutectic is situated at about 40 Or : 60 Ab (or perhaps 35–40 Or : 65–60 Ab), without possibility of giving the figures of the binary eutectic quite exactly.

According to some investigations made in 1912 by E. Dittler,[3] which, however, are only approximatives and not precision determinations, mixtures of Or and Ab show a lowering of the melting-point, which is greatest, namely almost 50°, at about 45–40 Or : 60–55 Ab, that is, close to the binary eutectic between Or and Ab as determined by the analytic-petrographic working method.

My young friend Olaf Andersen (from Christiania), formerly in the Geophysical Laboratory of Washington, told me that he proved, by investigations made in Washington but never published, that there is a lowering of the melting point for average

[1] In my explanation in this *Journal*, 1921, pp. 335–39, I assumed that Or had the same melting-point (1100°) as Ab. This is not quite a correct assumption. However, this has only a quite insignificant influence on the given view in the section just mentioned. (Written in the Winter, 1921–22.)

[2] My earlier analytic determination (in my treatise in *Tscherm. Min. Petr. Mitt.*, 24 [1905], about 40 (or 40–44) Or: 60 (or 60–65) Ab or Ab+An, do not count for the binary system but represent the eutectic boundary curve between Or and Ab+An at the presence of 10–25 per cent quartz etc.

[3] *Tscherm. Min. Petr. Mitt.*, 31, 1912.

mixtures of Or and Ab at about 50° below the melting point of Ab. On account of the extreme viscosity of the melts, it, however, was impossible to determine the exact lowering of the melting point.

It is to be noted that *Or and Ab* form a *mix-crystal-eutectic* whose melting point lies near 1050° (or some degrees above 1050°). We further notice that orthoclase crystallized in eruptive rocks (predominantly composed of an average mixture of Or and Ab which crystallized at a temperature only a few degrees below the melting curve between Or and Ab,) can take up by the temperature of the formation at least 55, possibly even 58 per cent or a little more Ab. On the other hand plagioclase crystallized under similar circumstances can absorb at least 25–30, and probably even a little over 30, per cent Or. In the crystallization of igneous rocks consisting of predominant Or+Ab with a quite subordinate admixture of ferromagnesian silicates, etc., there will therefore only be a very little jump chemically between orthoclase very rich in Na $AlSi_3O_8$ (Bröggers soda-orthoclase or soda-microcline) and albite or other plagioclase very rich in $KAlSi_3O_8$[1] (Rosenbusch's anorthoclase). When the two feldspars are formed at lower temperatures, the solubility in the solid phase of Ab in orthoclase (or microcline)

[1] I find it unnecessary in this very short résumé, which is based on Th. Vogt's lecture (April, 1920), and which I myself have completed with some further studies, to quote the numerous previous treatises on the very important problem here treated. I shall only mention a treatise by E. Mäkinen, Helsingfors, "Über Alkalifeltspäte" (*Geol. Fören. Forh.*, 1917), and by R. Herzenberg, "Beitrag zur Kentniss der Kalinatronfeltspäte" Diss. Kiel, 1911. H. A. Alling (see this *Journal* for 1921, No. 3) believes that "both the potash and the soda feldspars are dimorphous, each existing in two isomeric forms: each component crystallizing either in monoclinic or triclinic modification, depending on the temperature and the viscosity of the magma, that orthoclase and albite are high-temperature modifications and that microcline and possibly (?) barbierite are relatively low-temperature forms." This supposition cannot, however, be correct. The explanation advanced by Michel-Lévy, and later adopted and proved by Mallard, Rosenbusch, Groth, and Brögger, namely that orthoclase only is a cryptolamellic microcline, has now been given final proof, in that orthoclase and microcline show an identical Laue-diagram (Hadding, "Röntgenographische Untersuchung von Feldspat," *Lunds Universitets Aarsskrift*, Vol. XVII, 1921). And the mineral barbierite, a monoclinic soda feldspar consisting of $NaAlSi_3O_8$ with only small admixtures of Or and An, is no doubt based on a mistake.

and of Or in plagioclase (albit-oligoclase, oligoclase, etc.) is very remarkably diminished, as may be illustrated by the following:[1]

	Temperature of Formation	Percentage of	
		Ab (or Ab+*An*) in Orthoclase	Or in Albite Oligoclase-Albite, Oligoclase
Granite	About 900° (or 850°)	About 33	About 13
Granitic pegmatites	About 700° (or 750°)	About 30 (28)	About 10
Aplite veins	About 300–400°	Adularia about 15	Albite about 5
Low temp.		About 10	About 3 (?)

Most of the proper syenites—hence not including the nepheline- nor quartz-syenites—contain Or and Ab+*An* in proportions between 55 Or : 45 Ab+*An* and 30 Or : 70 Ab+*An*. That is, some have a relatively small surplus of Or, and others a similar relatively small surplus of Ab+*An* above the eutectic boundary between Or and Ab+*An*. In numerous syenites we find almost precisely the eutectic proportion of Or and Ab+*An*.

The binary eutectic between Ab and Ca Mg Si_2O_6, according to the investigations of *Bowen*,[2] lies at almost 100 per cent Ab and very little Ca Mg Si_2O_6. The extreme viscosity renders a precise determination impossible, but by extrapolation only a small (2 or 3) per cent Ca Mg Si_2O_6 might be estimated. The eutectic between Na, K-feldspar and aegirite—or a point on the eutectic boundary curve between Ab+Or and Na Fe Si_2O_6 with a little Ca Mg Si_2O_6 etc.—consists of

2.5 p.c. aegirite
97.5—Na, K-feldspar

(66 Ab with a trifle An and 34 Or).

This agrees with petrographic experience, viz., that the ferro-magnesian silicates (augite, amphibole, biotite, etc.) when their quantity in the syenites amounts at least to a small per cent (say

[1] See my treatise on the "Physikalisch-Chemische Gesetze der Krystallisationsfolge in Eruptivgesteinen," *Tscherm. Min. Petrogr. Mitt.*, XXIV (1905), pp. 528–42; further C. N. Warren, "A Quantitative Study of Certain Pertitic Feldspars," *Proc. Amer. Acad. of Arts and Sci.*, Vol. LI (1915), and Mäkinens' treatise of 1917.

[2] Amer. Jour. Sci., XL (1915).

6, 5 or perhaps even as low as 4 or 3 per cent) begin to crystallize at an earlier stage than the feldspar.

As little as 2 or a very few per cent of ferromagnesian silicate in the eutectic may only insignificantly diminish the temperature of the crystallization (as for instance 10 or 25°).

The conclusion is that the crystallization of syenites, in most cases containing only 5, 10 or up to 15 per cent of ferromagnesian silicates (presuming 1 atmosphere pressure and anhydrous melts) may have begun at about 1100°—in some cases up to about 1150°—and that the final solidification of the end-magma took place at a temperature a little below 1050°.

A small, as 2 to 6 or 8, per cent of quartz in quartz-gabbros, -norites, -diorites, or -syenites will bring about only a slight lowering of the temperature at the beginning, but a greater lowering at the close of the crystallization because there finally will result a granitic eutectic.

The granitic rocks.—Because the *binary* eutectic Or : Qu and Ab : Qu contains a considerable quantity (about 26 or 28 per cent) of quartz, we have to deal here with a decided lowering of the melting point, namely, 100° or a little more (as 125°) below the melting point of the given feldspar.[1] If the effect of pressure is left out of the question, the Or : Qu eutectic must be estimated at about 1100° or 1075°, and the eutectic Ab : Qu at about 1000 or 975°. For the *ternary* eutectic, Or : Ab : Qu, a temperature about 100° (or 125°) lower than for the binary eutectic Or : Ab, must be assumed, consequently about 950 (or 925°). The An contained in the plagioclase will occasion some increase in the temperature, but this rise is relatively small, since the plagioclase in the granites (albite-oligoclase, and oligoclase) as a rule only contains a small quantity of An.

Most granites (with 70–75 per cent SiO_2) contain between 20 and 28 per cent quartz, hence a little less or just about as much quartz as the eutectic boundary-line between quartz and K-feldspar +Na-rich plagioclase. Very rarely are the granitic rocks, including the quartz-porphyries and related rocks, so rich in silica that they contain even a small surplus of quartz above the eutectic.

[1] See p. 336 (and Fig. 3) in this *Journal* for 1921.

The relation between Or and Ab+*An* in granitic rocks lies with a few exceptions within the boundaries 0.7 Or : 0.3 Ab+*An* and 0.2 Or : 0.8 Ab+*An*. In about half of the heretofore published analyses[1] the proportions vary within the rather narrow boundaries, 0.5 Or : 0.5 Ab+*An* and 0.35 Or : 0.65 Ab+*An*. For a very large number we find almost exactly 0.4 Or : 0.6 Ab+*An*. The other components, besides quartz comprise a small percentage of Mg+Fe -silicates, magnetite, etc.

A very large number of the granitic rocks, chemically, lie very close to a complicated eutectic, Qu : Or : Ab+*An* : about 1 per cent ferromagnesian silicate and about 1 per cent magnetite, etc. The melting point,[2] when the temperature is recalculated to one atmosphere pressure and when H_2O, etc., is not taken into consideration, is not higher than about 950°, probably between 950° and 900°.

A small percentage of Mg+Fe-silicate, magnetite, etc., above the just mentioned complicated eutectic, will only raise the beginning of the crystallization a few degrees. A surplus of feldspar, in some cases orthoclase (microcline), in others a plagioclase rich in soda,—will raise it a small amount, say 50° or thereabouts. Hence, the crystallization in the most common granitic rocks (without a surplus of quartz), calculated at 1 atmosphere pressure and without regard to the H_2O, etc., of the magma, will not have begun at a higher temperature than 1000°, or, for rocks especially rich in Or, perhaps as much as 1050°. Most granitic rocks must have been quite fluid even a little below 1000. The conclusion of the crystallization will have taken place at a maximum of 950° and probably between 950° and 900°. In rocks with more than 75 or 76 per cent silica, the relatively small amounts of quartz present in surplus above the decisive eutectic, will raise the temperature of the beginning of the crystallization a little above the temperature of the

[1] As to the analyses published up to a few years ago, I refer to the statistic view—including about 600 analyses of granitic rocks—given in my treatise, *Anchi-monomineralische und anchi-eutektische Eruptivgesteine*, 1908, p. 75.

[2] Instead of melting *point* it should here, where the plagioclase as well as the ferromagnesian silicates are mixcrystals, be written: "A short distance on a eutectic boundary-line or-plane."

eutectic boundary line between Qu and the feldspars, but since the ordinary granitic rocks do not contain any significant surplus of quartz, the rise will be rather small.

We will now give a review of the temperatures (calculated at 1 atmosphere pressure and without regard to the contents of H_2O, etc., in the magma) at the beginning of crystallization of the silicate minerals for a number of igneous rocks.

Anchi-monomineralic rocks.—

Dunite.....About 1500°, occasionally 1550–1600°
Other peridotites with less olivine..About 1400°

Bronzite rocks.....About 1400°
Labradorite rocks.....About 1400–1450°
Bytownite rocks.....About 1475–1500°

Anchi-eutectic rocks.—

Gabbro and norite.....About 1250°
Diorite.....About 1200°
The most common syenites....About 1100°
The ordinary granites.....About 1000° (in part a little less)

We will here have to make two corrections: The pressure will occasion a rise, while the H_2O, etc., content on the other hand, will cause a lowering of the temperature of crystallization. The effect of pressure in lava flows may practically be neglected, and even in deep-seated rocks at 5 to 10 km. depth, the effect is very insignificant (see my treatise in this *Journal* for 1922, pp. 611–14). Even though the pressure of 5 to 10 km. depth raises the beginning of the crystallization of one mineral say 10°, and another say 40°, the difference between these figures is unimportant.

Different, however, is the effect of the light volatile compounds, H_2O, CO_2, etc., since these, when present in a noteworthy amount, lower the temperature of the crystallization remarkably. This lowering is nearly proportional to the amount of H_2O, CO_2 etc., in the same magma.

The content of H_2O, CO_2, etc., in the magmas of anorthosite, dunite, bronzite-rock, and other petrographically related anchi-

monomineralic[1] rocks, must, as explained in an earlier paper[2] generally, both absolutely and relatively, have been very little. We will, therefore, get only a small lowering of the temperature of crystallization on account of H_2O, CO_2, etc., in these rocks). Since the anchi-monomineralic rocks are always characterized by the presence of a mineral with a rather *high* melting temperature—such as labradorite, bytownite, olivine, orthopyroxene, diopside poor in iron, further nepheline, leucite, ilmenite, etc.,[3]—in so rich a quantity (as at least about 90 per cent) that the other components only bring about a rather small lowering of the melting point, the result will be that *these anchi-monomineralic rocks generally have a high temperature for the beginning of the crystallization, and this temperature is considerably higher than for the anchi-eutectic.*

Regarding the temperature of the *conclusion* of the crystallization, for instance in anorthosite and norite, on the other hand, we will have fair identity. There is this difference, however, that the eutectic end-magma of the anorthosites is present in a small quantity, while that of the norites is present in considerable abundance.

As we shall explain in a later paper, the high temperature at which the magmas of anorthosites and peridotites start to crystallize has a very important geological significance, because in my opinion, this causes these rocks never to appear as effusives, and causes the anorthosites—probably the dunites too—to be formed only in very deep-seated magma-basins.

For the *anchi-eutectic* magmas we may suppose a somewhat larger content of H_2O, CO_2, etc., and this content, as explained earlier[4] must have been relatively large, especially in the deep-seated *granitic* magmas.

[1] The sulphide ore segregations of typus Sulitjelma and Röros will not be considered here because these, as to the physico-chemical conditions of the genesis, occupy a separate place. See my résumé-treatise, *Die Sulfid-Silikatschmelzmassen*, 1918, p. 245, and the detailed description by Th. Vogt in his monography on "Sulitjelma" (*Norw. Geol. Survey*, now being printed).

[2] This *Journal*, 1922, p. 667–668.

[3] Here is not taken into consideration the segregation of nickel-pyrrhotite, with a relatively low melting temperature.

[4] See this *Journal*, 1922, p. 670–71.

Th. Vogt, in the lecture above quoted (April 16, 1920) in Christiania Videnskapsselskab, mentioned that the contents of light volatile compounds ordinarily must have been smaller in the effusive magmas than in the corresponding deep-seated magmas. Because the pressure increases the melting or the crystallization temperature much less than the volatile compounds lower it, therefore the deep-seated rocks in general, with perhaps some exceptions, will have crystallized at some lower temperature than the corresponding effusives.

Even if we do not consider the contents in the magmas of the light volatile compounds, the granitic magmas will show a lower temperature for the beginning of the crystallization than the magmas of any of the other more common rocks. Since we must assume that there is a larger amount of H_2O, CO_2, etc., in the granitic rocks than in the analogous magmas of the other more common rocks, we may draw the conclusion that *the granitic rocks are characterized by lower temperature for the beginning of the crystallization than are the other rocks*, perhaps with the reservation that there may be some rare igneous rocks of small extent where the temperature of the solidification is just as low or perhaps even a little lower than that of the granitic rocks.

R. A. Daly[1] states, "that the ordinary granites have been at least partly molten at a temperature no higher than 870°, nor lower than 575°." The first mentioned figure (870°) applies to the point of inversion between tridymite and α-quartz, but this point increases very remarkably with the pressure.[2] Consequently, the point of inversion determined at 1 atmosphere pressure cannot be used as a geological thermometer. The point of inversion between α and β quartz (at 1 atmosphere pressure = 575°) seems on the other hand to increase only very little with the pressure.[3] In this way we get a lower boundary at the conclusion of the crystallization.

The interval of the crystallization of granite-magmas—presumed waterfree and at 1 atmosphere pressure—is calculated to be between

[1] *Igneous Rocks and Their Origin*, 1914, p. 214.

[2] See this *Journal*, 1922, p. 620.

[3] See this *Journal*, 1922, p. 619.

about 1000° and 900°. In deep-seated magmas we will get a small addition to this, say 10–50° on account of the pressure, but on the other hand, a greater subtraction on account of the light volatile compounds. Therefore the crystallization will probably not have started at a higher temperature than about 950°, and for the relatively H_2O-rich anchi-eutectic magmas (delivering biotite and muscovite) we will probably have to count on only 900°. The conclusion of the crystallization may have taken place at a little lower temperature. The solidification of the granite therefore lies at about 900°; probably, for many granites even a little lower, say between 900° and 800°.

As to the granite-pegmatite dikes, with relatively large quantities of the light volatile compounds in the magma we will have to count on still lower temperatures; estimated by Th. Vogt at about 700°.

The great difference in the temperatures of the solidification of different igneous rocks can be illustrated as follows: two-thirds or three-fourths of an anorthosite magma solidifies at a temperature at which a gabbro-magma is still quite fluid, and a quartz-free gabbro is completely solidified at a temperature at which a granite magma has not yet started to crystallize (perhaps not considering the beginning of crystallization of certain telechemic minerals such as apatite, zircon, pyrite, etc.).

We will in conclusion point out the following: 1. The granites have the *lowest melting or crystallization temperatures* of all igneous rocks (at least of all the more common rocks). 2. As an end-product by the solidification of *quartz*-bearing gabbros, norites, syenites, etc., there results a *granitic* magma, which has often burst forth in the form of special dikes. 3. Granites belong to the *last epoch of the eruption* in the great petrographic provinces.

Points 2 and 3, as will be explained in a later paper, are due to the fact that magmas containing Qu as a special component (corresponding to more than about 55–60 per cent SiO_2 in the total rock) give by a differentiation of crystallization, according to our physico-chemical melting-diagrams, *a granitic magma* as the *end-product*.

On account of the physico-chemical facts we may draw the conclusion that this end-magma is characterized by a relatively

low temperature of crystallization. That this is true we have proved above in an empirical way.

We may note at the same time that a granitic magma, according to its history (as will be more fully explained in a later paper), *can never have been overheated above the upper boundary of the interval of the crystallization.*

Any hypothesis based on one hundred degrees or more of overheating of the granitic magma above the temperature at which the solidification began, must be rejected as unmaintainable.

THE TEMPORARY MISSISSIPPI RIVER[1]

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ORIGIN OF THE TEMPORARY MISSISSIPPI RIVER

The temporary Mississippi River referred to in the literature by Leverett,[2] Udden,[3] Carman,[4] Norton,[5] and others and published on the "Preliminary Outline Map of the Drift Sheets of Iowa, 1904,"[6] owed its existence to the displacement of the pre-Illinoian Mississippi by the Illinois glacial lobe which pushed its way westward into eastern Iowa.

[1] Published by permission of the director, Iowa Geological Survey.

[2] F. Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Survey, Mongraph XXXVIII* (1899), pp. 89–97; "Outline of Pleistocene History of Mississippi Valley, *Jour. of Geol.*, Vol. XXIX (1921), pp. 615–26.

[3] J. A. Udden, "Geology of Muscatine County," *Iowa Geol. Survey*, Vol. IX (1899), pp. 257–58, 350–57; "Geology of Louisa County," *op. cit.*, Vol. XI (1901), pp. 63–64, 108–9.

[4] J. Ernest Carman, "The Mississippi Valley between Savanna and Davenport," *Illinois Geol. Survey, Bull. 13* (1909), pp. 57–63.

[5] W. H. Norton, "Geology of Scott County," *Iowa Geol. Survey*, Vol. IX, 1899.

[6] *Iowa Geol Survey*, Vol. XIV (1903), Plate III.

DESCRIPTION OF COURSE OF THE TEMPORARY MISSISSIPPI RIVER

The advancing Illinoian glacier in crossing into Iowa from the east blocked the valley of Mississippi River and filled it with ice, damming the waters of the great river and necessitating the finding of a new course to the west. The stream found an opening by way of the Maquoketa River Valley and flowed first westward then southward through Goose Lake channel to the valley of Wapsipinicon River, and finally over the low divide between Mud and Elkhorn creeks to the valley of the Cedar at Moscow. Thence, continuing southward to the junction of Iowa and Cedar rivers at Columbus Junction, the combined waters of Mississippi, Maquoketa, Wapsipinicon, Cedar, and Iowa rivers, and those flowing from the edge of the ice, found their pathway obstructed on the one side by the great ice wall of the Illinoian ice sheet and on the other by the Kansan bluffs which stand 120 to 140 feet high. As the waters were unable to find an outlet, they rose and formed a large lake. Finding a low divide at Columbus Junction, the surplus water flowed by a devious course to the valley of Mississippi River below Fort Madison.

The course of the temporary Mississippi River is best described under the following heads: (1) Goose Lake channel, (2) Mud–Elkhorn–Mud Creek Valley, (3) Cedar River Valley between Moscow and Columbus Junction, and (4) abandoned channel south of Columbus Junction.

GOOSE LAKE CHANNEL

Goose Lake Channel (Fig. 1), which was first described by McGee,[1] comprises the northernmost part of the temporary Mississippi Valley and lies between Maquoketa River on the north and Wapsipinicon River on the south. The valley is well defined and ranges in width from one to approximately two miles. The valley walls, especially in the northern half, are cut into bedrock and rise from 70 to 200 feet above the flat valley floor, except toward the southern end, where they rise only about 25 feet. At the present time, Goose Lake channel is occupied by two small streams, Deep

[1] W J McGee, "The Pleistocene History of Northeastern Iowa," *U.S. Geol. Survey, Eleventh Ann. Rept.*, Part I (1899), p. 392.

Creek flowing north and Brophy Creek south, and in both cases, the creeks are very small in proportion to the size of the valley. The valley occupied by one stream continues across the very gentle divide at its head into that of the other without any constriction or in any way losing its identity. The divide between the two creeks, which has an elevation of about 670 feet above sea level, is so flat and poorly drained that a large marsh, formerly Goose Lake, covers its surface. Were it not for the fact that the creeks are seen to flow in opposite directions a divide would not be suspected.

Exposures in the channel are extremely few and those seen consist chiefly of horizontally stratified sand covered by loess. According to Carman,

> The surface material of Goose Lake valley passes downward into fine sand which is 60 to 100 feet thick on the divide south of Goose Lake. Farther north in Secs. 17, 8 and 5 of Deep Creek Township, Clinton County, several wells go 110 to 120 feet in sand and fine gravel. In the south part of the channel south of Elvira, wells 70 to 80 feet deep do not reach rock.[1]

MUD–ELKHORN–MUD CREEK VALLEY

For a distance of about fifteen miles westward from the south end of Goose Lake channel the temporary Mississippi River followed the valley of Wapsipinicon River to the debouchure of Mud Creek. This portion of the valley bears no particular name and calls for no special comment.

The name Mud–Elkhorn–Mud Creek Valley is applied to that part of the temporary Mississippi River course which lies between the mouth of Mud Creek on the north and the junction of Elkhorn–Mud Creek and Cedar River on the south, a distance of approximately thirty-six miles (Fig. 1). Like the Goose Lake channel, this valley also contains two insignificant streams, one flowing to the north and the other to the south. As the divide between the creeks in the Goose Lake channel is imperceptible and ill drained, so is that between the headwaters of Mud and Elkhorn creeks in the Mud–Elkhorn–Mud Creek Valley. Several large ponds and marshes cover its surface. It has an elevation of about 725 feet

[1] J. Ernest Carman, "The Mississippi Valley between Savanna and Davenport," *Illinois Geol. Survey, Bull. 13* (1909), p. 57.

above sea level. A noteworthy feature of the northern Mud Creek Valley is that the wide valley floor extends up into the tributary valleys so that the latter are exceptionally wide near their mouths. "It is believed that these broad flood plains (of the tributaries at their mouths) were filled from the main channel rather than aggraded by their own creeks."[1] The valley is not narrowed at the divide. A short distance from the divide the Elkhorn Creek Valley is divided by an island-like ridge into two branches, one trending southwest and the other more directly south. The first, which is the more conspicuous, has a direct course for more than two miles and a width of half a mile. Its valley walls are well developed and sharply outlined. The other branch, though wider, is less well defined and is more circuitous. West of Durant, where the branches reunite, the valley is well outlined for seven miles and ranges in width from a mile and a half to a little over two miles. It unites with the larger valley of Cedar River at Moscow. The valley walls, although more sharply defined at some places than others, merge gradually into the conspicuous feature of the valley, a wide terrace. The surface of this terrace is flat, and it is continuous except where crossed by the narrow valley of Mud Creek, 30 to 45 feet below the terrace surface.

Numerous exposures of sediment are found along the terrace banks of the southern Mud Creek between Moscow and Durant. The deposits seen in the various outcrops are of a uniform character. In the eastern half of the valley the sediments consist of finely laminated silts or clays, whereas in the western end of the valley the deposits are made up of fine stratified sands.

CEDAR RIVER VALLEY BETWEEN MOSCOW AND COLUMBUS JUNCTION

Between Moscow, Muscatine County, on the north and Columbus Junction, Louisa County, on the south is the unusually wide valley of Cedar River (Fig. 1). This valley is an extensive lowland surrounded on all sides by drift uplands which rise above it to the height of 80 to 100 feet. Its length is 24 miles and its width $5\frac{4}{5}$ miles. The valley is characterized by uninterrupted, wide, and monotonously even terraces, the upper surfaces of which

[1] W. H. Norton, "Geology of Scott County," *Iowa Geol. Survey*, Vol. IX (1899), p. 415.

MAQUOKETA
JACKSON
RIVER
MAQUOKETA
WAPSIPINICON
JONES
LINN
RIVER
CEDAR RAPIDS
CLINTON
GOOSE LAKE CHANNEL
LYONS
CLINTON
CEDAR
JOHNSON
TIPTON
IOWA CITY
SCOTT
WEST LIBERTY
MUD CREEK
MUD-ELK HORN VALLEY
DAVENPORT
MUSCATINE
LAKE
CALVIN
MUSCATINE
WASHINGTON
ILLINOIS
WASHINGTON
COLUMBUS JUNCTION
LOUISA
WAPELLO
WINFIELD
MISSISSIPPI
RIVER
HENRY
MOUNT PLEASANT
DES MOINES
SKUNK
RIVER
BURLINGTON
ARANOKEE
DES MOINES
RIVER
VIELE
FORT MADISON
KEOKUK
MAP SHOWING THE
COURSE OF THE TEMPORARY
MISSISSIPPI RIVER
WALTER H. SCHOEWE

FIG. 1

rise from 25 to 40 feet above the flood-plain of Cedar River. Although the slope is not apparent to the eye, the terraces have a gentle inclination to the south. The surface of these terraces is approximately 660 feet above sea level at their northern extremity at West Liberty and Moscow, and from these points they slope gently to their southern extremities in Louisa County, 18 miles distant, where they have an elevation of 615 feet. Scattered over the entire area, but especially in the vicinity of Cedar River, there are low-lying sand mounds or dunes. On the west side of Cedar River, the terrace is remarkable for its uniform width, since out of the $22\frac{1}{2}$ miles of its total length, it maintains for a distance of 14 miles an average width of $4\frac{3}{4}$ miles. Here also, the terrace is continuous for its entire length, but, on the east side of the river, it is broken into nine remnants. Immediately west of Moscow, on the west bank of Cedar River, is an island-like highland which is a half mile distant from the main upland to the northwest, the surface of which rises, on the average, 75 feet above the level top of the surrounding terrace. This upland remnant has an area of about $1\frac{1}{2}$ square miles. The bluff line on the north and east is cut into the Devonian limestone and is therefore very well defined. Toward the south, and especially toward the southwest, the border of the remnant is less conspicuous, due to the presence of numerous sand dunes.

Exposures of the materials in the terraces are not numerous, because of the extreme youthfulness of the topography and the slight relief of the region. The surface materials consist of fine yellowish to brownish or drab-colored loess-like silt and sands, the latter forming the dune areas previously described. A few scattered bowlders dot the terrace surface. Most of the wells on the terrace are about 30 feet deep, but one at Nichols is recorded to have penetrated at least 250 feet[1] of unconsolidated material. The various outcrops, for the most part, show a fine- to medium-grained white to light-brownish sand, the strata of which in the northern part of the terrace are thin and essentially horizontal. Farther south, the sand shows cross-bedding and numerous thin layers of pebbles, the largest of which have a diameter of less than 1 inch.

[1] J. A. Udden, "Geology of Muscatine County," *op. cit.*, Vol. IX (1899), p. 355.

ABANDONED CHANNEL SOUTH OF COLUMBUS JUNCTION

The abandoned channel south of Columbus Junction was discovered by Leverett as early as 1896. This channel, which is outlined on Figure 1, has been described in detail by Leverett in his monograph on the Illinois glacial lobe.[1] The channel extends southward from Columbus Junction for a distance of 12 miles to the vicinity of Winfield. Separating into two branches at this point, its course continues westward to the valley of Skunk River at Coppock. Thence the temporary course of the Mississippi is southward for a distance of 18 miles to the bend of the Big Cedar, where it leads southeastward across Lee County to the valley of Mississippi River at Viele, 6 miles below Fort Madison.

This ancient valley of the Mississippi is incised below the general upland surface of the Kansan drift plain 30 to 60 feet. The valley floor rises 120 feet above the level of Iowa River at Columbus Junction, where it lies at an elevation of about 700 feet above sea level. Its general width ranges from $1\frac{1}{4}$ to $1\frac{1}{2}$ miles. The valley is well defined but is more conspicuous the farther southward it is traced. At the divide in Sections 35 and 36 of Elm Grove Township, Louisa County, 7 miles south of Columbus Junction, the valley floor is 1 mile wide and 35 to 40 feet below the general upland level. Several miles south of Columbus Junction bedrock appears in the valley walls and that part along Skunk River is cut largely in solid rock. It has been estimated that the excavation along the channel from Columbus Junction to Viele amounts to one-half a cubic mile.[2] Unusual deposits of sand and gravel are lacking in the channel.

VIEWS REGARDING THE DURATION OF THE TEMPORARY MISSISSIPPI RIVER

Concerning the general displacement of the Mississippi River by the Illinoian ice sheet, Leverett states that "with the recession of the Illinoian ice sheet the Mississippi shifted to its present course between Clinton and Fort Madison.[3] And in speaking particularly

[1] F. Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Survey, Monograph XXXVIII* (1899), pp. 91–93.

[2] F. Leverett, *op. cit.*, p. 93.

[3] F. Leverett, "Outline of Pleistocene History of Mississippi Valley," *Jour. of Geol.*, Vol. XXIX (1921), p. 622.

of the abandoned channel south of Columbus Junction, he states that

> The abandonment of the lower end of the channel from Columbus Junction southward probably cocurred as soon as the ice sheet had withdrawn sufficiently to uncover the present line of the stream, for the altitude along the present Mississippi bluffs is a few feet lower than the beds of the abandoned channel. This lower altitude along the Mississippi is due to the incomplete filling of the preglacial channel by drift.[1]

Concerning Goose Lake channel, he concludes that its occupancy "may have continued down to Wisconsin time."[2] Carman[3] is of the opinion that Goose Lake channel and Mud–Elkhorn–Mud Creek Valley were followed for only a short time after the retreat of the Illinoian ice sheet. Udden[4] also does not favor the view that the channel south of Columbus Junction was occupied for any considerable time, although he is of the opinion that Mississippi River did follow the Cedar River part of the temporary Mississippi River until the Iowan ice incursion. Udden believed that Cedar River Valley between Moscow and Columbus Junction had lost its river-like character and had taken on the form of a lake very similar to that of Lake Pepin in the Mississippi River at the mouth of the Chippewa River. To this wide expanse of water, Udden gave the name "Lake Calvin" in honor of its discoverer, Samuel Calvin.

Recent work by the writer on the origin and history of extinct Lake Calvin has convinced him that the former Mississippi River followed the westernmost course for a long period of time, perhaps to the time of the Iowan glaciation.

NEW FACTORS BEARING ON THE DURATION OF THE TEMPORARY MISSISSIPPI RIVER

The duration of the temporary Mississippi River involves two factors which up to the present time have received no consideration. They are (1) extinct Lake Calvin and (2) Illinoian gumbotil.

[1] F. Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Survey Monograph XXXVIII* (1899), pp. 96–97.

[2] F. Leverett, "Outline of Pleistocene History of Mississippi Valley," *Jour. of Geol.*, Vol. XXIX (1921), p. 622.

[3] J. Ernest Carman, "The Mississippi Valley between Savanna and Davenport," *Illinois Geol. Survey, Bull. 13* (1909), p. 62.

[4] J. A. Udden, "Geology of Muscatine County," *Iowa Geol. Survey*, Vol. IX (1899), p. 355.

EXTINCT LAKE CALVIN

Lake Calvin was formed at the time of the third or Illinoian ice invasion. The great ice sheet coming from the state of Illinois found its way westward, filled the valley of the Mississippi River, and advanced into the southeastern border counties of Iowa. In its advance, the mighty river had to abandon its course and was forced to find the new one described above. As the present course of Iowa-Cedar River was occupied by the great ice mass forming a dam across its valley at Columbus Junction, the combined waters of Mississippi, Maquoketa, Wapsipinicon, Cedar, and Iowa rivers and those flowing from the edge of the ice were ponded back, giving rise to the large lake labeled "Lake Calvin" on Figure 1. During the long existence of the lake, the surplus water found its way to the unfilled valley of the Mississippi below Fort Madison by way of the abandoned channel south of Columbus Junction.

The shape of the basin formerly occupied by Lake Calvin, considered in broad, general outline, is that of a huge letter V, made irregular by numerous ramifications, especially in the northern part of the lake site. The arms of the V extend in directions parallel to Iowa and Cedar rivers, and meet near the junction of the two streams at Columbus Junction, Louisa County.

Without including the numerous river-like irregularities north of Iowa City, West Liberty, and Moscow as part of the lake basin proper, the lengths of the Iowa and Cedar river arms of the V are 28 and 24 miles, respectively, with corresponding average widths of 4.4 and 5.8 miles. The widest portion of the old lake is $2\frac{1}{2}$ miles south of Lone Tree, where the bluff lines are separated by a low, flat stretch of country nearly 15 miles wide. At the time of their greatest expansion, the waters of the lake covered an area of approximately 325 square miles.

The site of former Lake Calvin, which is now an extensive lowland, has been described on pages 423 and 425. At least three sets of terraces occur in the lake basin, two of which represent the ancient floor of the lake. Laminated silts 35 feet thick characterize the lake terraces, whereas sand and gravel with typical fluvial cross-bedding and pocket-and-lens type of structure mark the third terrace.

Although known to Calvin[1] as early as 1874, partially mapped and described by Udden[2] in 1899, and noticed by Leverett[3] in the same year, conclusive evidence of the existence of Lake Calvin had not been presented until the writer[4] completed his studies on the origin and history of extinct Lake Calvin in 1919.

ILLINOIAN GUMBOTIL

So long as Lake Calvin existed, the Mississippi must have followed the temporary course outlined on the previous pages. Hence any evidence favoring a long life for the lake must favor at the same time a long duration for the temporary Mississippi River.

The duration of Lake Calvin is intimately related with the formation of the Illinoian gumbotil. For, as it will be shown, the lake could not have been drained until after the gumbotil was formed and the valleys of Iowa-Cedar and Mississippi rivers were developed. It has been shown by Kay[5] that in the formation of any gumbotil a very long period of weathering of the till is required and that during this period of weathering erosion is very slight. That the formation of the gumbotil is an exceedingly slow process is indicated by the fact that no gumbotil is found on the Iowan and Wisconsin drift sheets which are believed to be too young to have had a gumbotil developed on them.[6] The Illinoian gumbotil is on the average 5 feet thick.

During the very slow process of weathering of the till to form the Illinoian gumbotil, erosion was very slight. It is inconsistent with the theory of the formation and origin of the gumbotil that valleys sufficiently deep to drain the lake would have permitted the formation of the Illinoian gumbotil to the very edges of the valley walls. Especially is this true as the gumbotil lies in a horizontal plane and does not conform to the surface slopes produced

[1] J. A. Udden, *op. cit.*, pp. 352–53.

[2] *Op. cit.*, pp. 246–388.

[3] F. Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Survey Monograph XXXVIII* (1899), pp. 89–97.

[4] W. H. Schoewe, "The Origin and History of Extinct Lake Calvin, Iowa," *Iowa Geol. Survey*, Vol. XXIX, 1919. (In press.)

[5] G. F. Kay, and J. N. Pearce, "The Origin of Gumbotil," *Jour. of Geol.*, Vol. XXVIII (1920), pp. 89–125.

[6] *Op. cit.*, p. 124.

by erosion. From this one is forced to the conclusion that the gumbotil formerly extended across the valleys. It is conceivable, although there is no evidence for it, that Lake Calvin might have had an outlet across the Illinoian upland plain immediately after the ice withdrew without having involved much erosion and interfered with the formation of the gumbotil. That such could have been the case for any considerable length of time, however, is not probable. The level of the lake during its maximum height stood 120 feet above the present surface of the Iowa-Cedar River at Columbus Junction. The surface of the lake could not have been lowered appreciably without having resulted in pronounced erosion, which would have been fatal to the formation of the gumbotil. The presence of the lake, on the other hand, is fully in accord with the theory of the formation of the gumbotil, for the levels of the lake and of the gumbotil as they are shown at Columbus Junction are separated by not more than 10 feet, a difference in height which would hardly permit pronounced erosion.

The Illinoian gumbotil underlies the flat tabular stream divides and outcrops near the valley walls of Iowa-Cedar River and along both sides of the Mississippi, high above the present level of the rivers. This together with the fact that the gumbotil lies horizontally clearly shows that the present valleys of Iowa-Cedar and Mississippi rivers are incised below the general Illinoian upland plain and thus are post-Illinoian gumbotil in age. Therefore these valleys through which the lake was eventually drained could not have served as the outlet of Lake Calvin very soon after the ice had retreated. Thus Lake Calvin existed for a long time, and the displaced Mississippi must have followed the course south of Columbus Junction until the lake was finally drained by way of the Iowa-Cedar River Valley.

It appears that the earlier investigators based their conclusion of an early abandonment of the temporary course of Mississippi River south of Columbus Junction on three facts: (1) that there are no unusual deposits of sand and gravel in the now abandoned channel south of Columbus Junction; (2) that the elevation of the Illinoian upland bordering the present course of the Mississippi is only a few feet lower than the bed of the abandoned channel; and (3) that

the abandoned channel is not as well developed as Goose Lake channel.

It is commonly recognized that during the maximum advance of the Illinoian ice sheet the displaced Mississippi followed the course outlined in the preceding pages. On the assumption that a river occupied the valley of Iowa and Cedar rivers instead of Lake Calvin, the absence of the fluvial deposits can readily be accounted for by supposing that the stream has changed its course at Columbus Junction. On the other hand, if the filling up of the Iowa and Cedar River valleys is due to stream deposition, there appears no logical reason why deposits similar to those found north of Columbus Junction and in the Mud–Elkhorn–Mud Creek Valley should not be seen in the abandoned channel. There is no reason to believe that the streams were no longer overloaded when the waters used the channel, or that erosion has subsequently removed materials which may have been deposited there. The absence of such deposits demands explanation. A plausible and adequate explanation is offered by the supposed former existence of Lake Calvin. A lake acts as a filtering plant for a river, and accordingly it is easy to account for the absence of the fluvial deposits in the abandoned channel if Lake Calvin really existed and this channel served as its outlet. For comparison the streams emptying into and draining the Great Lakes may be cited. It is well known that many of the streams emptying into the Great Lakes are more or less discolored and muddy by reason of their load of sediment. Also it is true that such streams as the Niagara and the St. Lawrence which flow outward from the lakes are relatively free from sediment, and hence have little erosive power. Because of the settling of sediments in the lake basin and perhaps also because the ground in which the abandoned channel was excavated may have been frozen as suggested by Chamberlin,[1] it is not to be expected that the outflowing stream would have much erosive power nor much material to deposit. The absence of any considerable deposits of sand and gravel within the channel is then quite natural. This too may explain why this abandoned channel is not so well developed as the Mud-Elkhorn-Mud and Goose Lake channels.

[1] F. Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Survey Monograph XXXVIII* (1899), p. 93.

The fact that the Mississippi bluffs are a few feet lower than the bed of the abandoned channel does not preclude the drainage of the lake by way of the abandoned channel south of Columbus Junction. The Illinoian-Mississippian sag, if it really existed, was at least 20 miles distant from Lake Calvin by way of the present Iowa-Cedar River Valley. What the elevation of the intervening topography may have been is not known. The Illinoian upland at Columbus Junction is about 730 feet above sea level; at Morning Sun, only $2\frac{3}{4}$ miles from the south valley wall of Iowa-Cedar River, it is 752 feet; and at Newport, only 2 miles south of the river bluffs, it is at least 720 feet. The Mississippi bluffs north of Wapello are at many places over 700 feet above sea level. The Illinoian drift plain forms the upland surface on either side of the present course of the Mississippi, and Illinoian drift and gumbotil are exposed within several feet of the upper surface, high above the present level of the river. This clearly shows that the present valley of Mississippi River is incised below the general Illinoian upland plain and thus is post-Illinoian gumbotil in age. The same is true of the Iowa-Cedar River Valley.

On the basis of erosion alone it is not apparent why the Mississippi should have shifted its course to its present valley between Clinton and Fort Madison "with the recession of the Illinoian ice sheet."[1] All pre-Illinoian drainage lines must have been filled with drift, if not completely, at least partially, by the depositing Illinoian ice sheet. This is indicated by the presence of the gumbotil along the valley walls of the streams. According to Leverett, the altitude along the Mississippi bluffs is but a few feet lower than the bed of the abandoned channel which at Columbus Junction is 120 feet above the level of Iowa River. Hence an enormous amount of material must have been removed before the displaced Mississippi River could have returned to its former course. The process of removing this material must have involved a long time.

[1] F. Leverett, "Outline of Pleistocene History of Mississippi Valley," *Jour. of Geol.* Vol. XXIX (1921), p. 622.

REVIEWS

The Laramie Flora of the Denver Basin. By F. H. KNOWLTON. United States Geological Survey, Washington, *Professional Paper 130*, 1922. Pp. 175, pls. 27.

The Introduction deals with a history of Knowlton's investigations of the Laramie flora, which were begun in 1889. His original intention was to study the flora of the Laramie formation of the entire Rocky Mountains. The older collections, which had served as a basis for the work of Lesquereux, Newberry, and others, were to be critically reviewed, and the new material was to be added, but the unsettled condition of opinion regarding the Laramie group delayed the carrying out of this plan, and it was finally decided to restrict the study to an area about which there is little or no disagreement. Such is the Denver Basin in Colorado.

The paper deals with the plants known from the Laramie of the Denver Basin, the material being derived from many sources. While very considerable collections were brought together, Knowlton states that the flora is neither large nor very impressive, because the fossil plants of the Laramie are rarely found in great abundance. The matrix in which Laramie plants occur is usually a soft, friable sandstone which is not fitted to retain plant impressions with fidelity, and it is difficult to find perfect specimens. In attempting to present as complete a picture as possible of the plant life of the time, it has frequently been necessary to describe forms on rather slender data. But they are all figured and described adequately enough to be recognizable in the future.

Part I gives a historical review of the Laramie problem; Part II discusses the geologic relations and flora of the Laramie of the Denver Basin; and Part III deals with the Laramie flora itself. A complete list of the Laramie plants in the Denver Basin is given, together with various synonyms and changes of interpretation. The following genera are predominant in the flora:

Pteris	*Magnolia*
Sequoia	*Laurus*
Cycadeoidea	*Cinnamomum*
Juglans	*Platanus*

Hicoria	*Cercis*
Myrica	*Pistacia*
Salix	*Ilex*
Quercus	*Rhamnus*
Artocarpus	*Zizyphus*
Ficus	*Cornus*
Aristolochia	*Fraxinus*
Nelumbo	

Ferns were not very abundant as individuals, but diversified in type, and represented by eight genera and fourteen forms. The conifers appeared to have been an unimportant element. The only example belonging to the Cycadaceae is the beautifully preserved small trunk now referred to as Cycadeoidea. The monocotyledons were apparently not an abundant element during the Cretaceous period, and the Laramie flora is no exception. The dicotyledons were, of course, the most abundant and diversified elements of this flora.

Knowlton draws the following tentative conclusions as to the climatic conditions under which the Laramie flora may have existed. It seems to him beyond question that there must have been plenty of moisture on account of the abundant presence of coal and the apparent requirements of the majority of plants enumerated in his lists. It also appears to him a natural conclusion that the climate was warm, at least warm temperate.

Knowlton dwells at length upon the geologic relations of the flora, a feature which makes his paper particularly interesting for the geologist. He compares the Laramie flora with the Montana flora, Denver formation, Arapahoe formation, Lance formation, uppermost Cretaceous of the Atlantic Coastal Plain, Patoot Series of Greenland, and the Upper Cretaceous of Europe.

A. C. N.

Mineralogy of Pennsylvania. By SAMUEL G. GORDON. Special Publication No. 1, Academy of Natural Sciences, Philadelphia, 1922. Pp. 255, pl. 1, figs. 110.

Pennsylvania's mineral localities have been combed by generations of enthusiastic specimen hunters until there is scarcely a large collection anywhere in the world that does not include representatives from some of the famous localities of the state: Falls of French Creek, Wood's Chrome Mine, the Gap Nickel Mines, or the old lead mines of Phoenixville. The Pennsylvania Piedmont, with its great variety of rock types crowded into a small triangle in easy reach of Philadelphia, furnished a readily accessible collecting ground at the period when mineralogy was

experiencing its most rapid growth in this country. The classic localities have afforded type specimens that have woven themselves into the very fabric of the science.

The present volume sums up a wealth of published data and adds much original material gained through a decade of field and laboratory study. The book consists of two main divisions: the first takes up the mineral species in Dana's order with physical and chemical data and a list of localities for each species. While much information is repeated from standard mineralogies, the compactness and completeness of the data justify the duplication. All reliable and "semi-reliable" chemical analyses of Pennsylvania minerals have been included. Cuts from a variety of sources illustrate crystallography. In the second part of the book, the localities are described by counties and townships. A valuable feature of the book is the use of the Kemp co-ordinate system so that by a figure of four digits any spot may be located accurately on a topographic atlas sheet. The minerals under each locality are listed by paragenetic classes.

While considerable emphasis is placed upon paragenesis, economic geologists would probably have liked to see this phase given even more attention. The class "hydrothermal deposits," for example, is not subdivided, and veins of high and low temperature are grouped together. For some localities data are doubtless lacking, but for French Creek, Cornwall, and many other deposits, the author has sufficient first-hand acquaintance with conditions to have given his readers some interesting observations on mineral sequence.

An introductory chapter on "Origin and Occurrence of Minerals" gives a concise résumé of geologic processes. The statement (p. 4) that kaolin may be formed by hydrothermal metamorphism may be questioned. Tennantite is classed as an arsenide, although enargite is correctly described as a sulpharsenate. The growing number of believers in the hypogene origin of much bornite and some chalcocite would object to the omission of these minerals from the list of primary sulphides. Pyrrhotite is a serious omission from the list of primary iron minerals.

It is interesting to note that the author places rhodonite and tephroite among dynamic metamorphs (Iron Manganese Zinc Deposits) and not among contact or hydrothermal minerals, a viewpoint rather in accord with that of Palache,[1] who has made exhaustive studies of the minerals of Franklin, New Jersey, than with the recently published discussion by Ries and Bowen.[2]

[1] Unpublished discussion.

[2] "Zinc Ores of Sussex County, New Jersey," *Econ. Geol.*, Vol. 17, pp. 517–71.

Another chapter compiles in tabular form the salient features of the geology of Pennsylvania. The author considers the much discussed Wissahickon Gneiss as Ordovician in accordance with Rand[1] and not as pre-Cambrian as claimed by Bascom[2] and by Bliss and Jonas.[3]

A pleasing feature of the book is its exceptional freedom from typographical errors, particularly when it is considered that so many proper names have been used. A native of Chester County might offer the objection that Comley Hall was a man, not a building (p. 168: "field northwest of Comley Hall"), or a German might criticize the spelling: "regelmäfsig," but remarkably few mistakes of this sort are to be noted. The accuracy in the descriptions of localities will be best appreciated by those who have spent days in trying to locate some overgrown exposure from the vague information given by the older writers.

A fuller table of contents would have added to the convenience of the volume—the one used consists of only seven lines. The index, however, is adequate.

Not only will the work be indispensable to Eastern mineralogists and collectors but its mineral lists will prove of interest to economic geologists. A recent paper on the chalcocite of Bristol, Connecticut, has brought home the fact that much is to be learned from the old mines of the Eastern States. Pennsylvania localities, with their unusually complete lists of species and the elaborate suites of specimens available in many museums, offer attractive opportunities for paragenetic studies.

H. E. McKinstry

Casapalca, Peru

Physiography and Glaciology of Middle West Greenland. Abstract of part of results of Swiss Greenland Expedition. By Alfred de Quervain, P. L. Mercanton, and others. Ergebnisse der Schweizerischen Grönlandexpedition, 1912–1913. Denkschriften der Schweizerischen Naturforschenden Gesellschaft. Bd. 53. Zurich, 1920. Pp. 402, maps, diagr., photos.

The physiographic studies made along the front of the inland ice of Greenland in the vicinity of Jakobshavn by the Swiss expedition, are of exceptional interest as showing the conditions which may have obtained on the glacial fronts of America and Europe not many thousand years

[1] "Notes on the Geology of Southeastern Pennsylvania," *Proc. Acad. Nat. Sci., Phila.* XLIV (1892), pp. 174–202.

[2] Philadelphia Folio, 162, *U.S. Geol. Survey.*

[3] Prof. Paper 98-B, *U.S Geol. Survey*, 1916.

ago. Some of the striking features may be noted. The banding of the ice, apparently representing the annual layers, became steeper and steeper toward the edge, till it was nearly vertical near the frontal moraine. At many points in the lee of the frontal moraine there was such a collection of drifted snow blown off the ice-sheet that parasitic glaciers formed. The bare rocky zone beyond was deeply gouged and lake-filled. The difficulties of travel were increased by cryoconite, or the well-known dustwells, which pit the ice in some locations covering a quarter of the area. They occur in a zone within 10 km. of the west front of the ice. These dust wells consist of water-filled cylindrical tubes, mostly 5–10 cm. in diameter and 40–50 cm. deep, which contain earthy material on the bottoms. They have been formed by the melting induced by the extra heat absorbed by the dark covering of debris. The material has the fine-grained character of aeolian deposits, which appear to have been concentrated by flowing water on the surface.

The surface west of the ice-sheet was all glaciated except for an occasional high peak, above an altitude of 1,000 or 1,050 m. in the vicinity of Sermilikfiord, or above 1,300 m. far to the northeast. [On the sides of the east Greenland Sermilikfiord the continental glaciation extended up to 800 m.] The rugged peaks above the reach of the ice-sheet were in marked contrast to the rounded lower slopes eroded by the ice. In spite of active rock decomposition, the traces of glaciation were surprisingly fresh. Most striking were (*a*) the thinness and rarity of veneers of drift, (*b*) the intensity of the attack of the ice on the bed rock, and (*c*) the persistence of glacial polish. Erratics were in some cases well weathered, though resting on surfaces wh.ch were still smooth. The old striae were generally from the S.E., though the latest ones, from the thinner ice, crossed these generally from the east, the direction of the local slope. Both on the east and west coasts of Greenland large sections of rock have slid over the polished surfaces in front, making terraces with polished tops.

Evidences of local glaciers after the retreat of the main ice-sheet were found, especially in the south. Farther north the mountains were too low and the precipitation too small for such local glaciers to form. In the vicinity of Sermilikfiord (lat. 65° 30′—65° 40′) glaciers were found filling all the valleys. They were fed from extensive accumulators wherever the altitude exceeded 1,000 m. It seemed likely from Danish charts that this local ice extended northeastward all the way to the inland ice 100 km. away. These coastal glaciers were evidently not relics of the inland ice for, though the moraines were considerable, they did

not show signs of extensive retreat. In 1912, however, the glacial fronts seemed to be generally receding. Three glaciers of Blaesdal, Disco Island, were found to have retreated during the past fifteen years, continuing a preceding recession.

Marine terraces gave other evidence of local glaciation. In the vicinity of Kuk (lat. 66° 48′ N., long. 52° 17′ W.) and Sarfanguak, the lowest terrace was at 40 m. above sea-level, and was composed of a layer of till, covered with marine-laid sediments, another layer of till, and a top layer of mussel-bearing sand. Evidently, during the formation of these deposits, the land was depressed and the tongue of the valley glacier supplying the sediments retreated, advanced, and retreated again. The character of the fossils indicates a climate at that time too warm to have been associated with inland ice as far out as this.

The expedition was able to make some valuable observations of icebergs. Icebergs, even though tabular at the start, usually were so melted and exploded that they did not reach the open sea as large masses. Many bergs carry portions of sub-glacial caverns, which are visible in various stages of destruction. Calving takes place by hydrostatic lifting, or by falling or pushing off. As this occurs there is much exploding from the sudden release of the highly compressed air in the glacier. This air goes into the glacier with the original snow, and the increasing weight piled on top of it brings on enormous compression which, when suddenly released by calving, hurls a berg into a thousand pieces in successive explosions. In Disco Bay the sizes of icebergs ranged up to 75 m. high and 640 m. long.[1]

CHARLES F. BROOKS

Earth Evolution and its Facial Expression. By WILLIAM H. HOBBS: Pp. xvii+178, plates 6, figs. 84. New York: The Macmillan Co., 1921.

This volume of 178 pages is well printed on good paper, and is illustrated with many diagrams and sketches. Although it seems to be addressed to the general reader, it is rather too technical for any but trained students of the earth sciences.

In the opening chapters, the author outlines the progress of ideas regarding the state and origin of the earth, and concludes that Laplace's theory is now generally discredited, while that of Chamberlin "has the most general support among students of earth science." He also decides

[1] A discussion of the maintenance and ablation of the inland ice is included in a review published in the *Geographical Review*, July, 1923.

in favor of those who consider that the earth is made of nickel-iron enveloped in stony meteoritic material and kept in a rigid state by pressure.

The author is convinced that igneous magmas are the result of the fusion of shales and other sedimentary beds locally where occasional relief of pressure permits. Such relief is explained in two ways—the rising of a competent stratum in an anticline, and under uplifted fault-blocks. He argues that laccoliths are of this origin. Apparently batholiths are merely enlarged or coalesced laccoliths. He regards these domes as the initial stage in the forming of large anticlines and supposes that the Colorado-Montana region affords proof of the theory. To this end he is obliged to redate the pre-Cambrian granites of the anticlinal cores and put them in the late Cretaceous; but unfortunately the field facts are conclusively against him.

As to the mode of egress of magma thus formed, he agrees with Daly that blowpiping by gases and vapors which collect at the crown of the laccolith, is the chief process. These gases are not "juvenile" but are acquired from the shales fused and from rocks invaded during the ascent.

Turning to the general deformation of the earth, the author not only accepts the tetrahedral theory, of which the book gives a good summary, but he adds a novel modification of it, whereby the earth is supposed to have developed a twinning along a plane following the ancient Sea of Tethys. This left the hypothetical Paleozoic continents of Atlantis and Gondwana protruding to the north and south. Why this twinning did not affect the earth in earlier and modern times is not explained. The author ridicules those timid persons who suspect the existence of narrow land bridges from continent to continent in earlier periods in order to account for the strange distribution of faunas and floras past and present, and favors the bolder idea that the existing ocean basins have been made in large part by the collapse of the Permian continents, especially in the Atlantic and Indian regions.

The mountain arcs of southeastern Asia are interpreted as young anticlines—not overthrust from the land, as Suess presumed, but underthrust from the ocean basins. In this he seems not to have been aware of the earlier writings of Chamberlin and others regarding the sinking of the oceanic sectors resulting in the crowding of the continental borders. His argument is by no means convincing, and the experimental illustration fails because the photograph of the apparatus is not clear.

The forms of the arcs in plan are then discussed, but if there is in the chapter anything deserving to be called an explanation, the reviewer has

not found it. The position of the arc is said to be determined by the frontal slope of the mud lense built outward along the continental shelf. This soft yielding mass is apparently supposed to behave as the stiff rod, bent in the middle, which the author cites for comparison. The arcs are believed to have been formed in succession from the old coign outward.

The theory is said to explain the sequence of lavas, in such regions as the American Cordillera, from andesitic to rhyolitic and basaltic, and also the facts of distribution of lavas in comagmatic regions. The first fusion is supposed to affect the "average" shale and thus form an andesitic magma. Later the fusion spreads to layers of siliceous shale on the one hand and calcareous shale on the other, and from these are derived the constitutents that change the original magma to siliceous or basaltic composition. This is considered typical of the regions of active folding.

On the other hand the regions where the author believes faulting to be dominant, such as the Atlantic basin, are characterized by basaltic and alkaline lavas. The prevalence of these is explained by supposing that, in the process of faulting, a massive competent layer of limestone generally tends to separate from an underlying layer of calcareous shale. This, being relieved of pressure, liquifies and forms a basic magma.

In his concluding chapter, the author comments upon the tendency of most scientific men to sanctify certain theories, and their tardiness in recognizing the consequences of the passing of a discarded theory.

Like previous works by the same author, the book is interesting and suggestive, and it also reveals the same defects of loose reasoning, inaccurate understanding of field facts and earlier writers, and hasty conclusions.

ELIOT BLACKWELDER